UNIVERSITY OF WATERLOO

School of Computer Science

CS 343
Concurrent and Parallel Programming

Course Notes* Fall 2024

https://www.student.cs.uwaterloo.ca/~cs343

μC++ download or **Github** (installation: **sudo sh u++-7.0.0.sh**)

August 29, 2024

Outline

An introduction to concurrent programming, with an emphasis on language constructs. Major topics include: exceptions, coroutines, atomic operations, critical sections, mutual exclusion, semaphores, high-level concurrency, deadlock, interprocess communication, process structuring on shared memory architectures. Students learn how to structure, implement and debug complex control-flow.

Contents

1 Advanced Control Flow (Review)

- *Within* a routine, basic and advanced control structures allow virtually any control flow.

- For predicate only, **while** and **for** are interchangeable.

GOOD	GOOD

`while ( predicate ) {`
`    S1`
`}`
	`for ( ; predicate ; ) {`
	`    S1`
	`}`

  for allows adding/removing loop index for debugging.

- Do not use **while** to simulate **for**.

BAD	GOOD

`int i = 0;`
`while ( i < 10 ) {`
`    S1`
`    i += 1;`
`}`
	`for ( int i = 0; i < 10; i +=1 ) {`
	`    S1`
	
	`}`

- **Multi-exit loop** (or mid-test loop) has one or more exit locations occurring *within* the body of the loop, not just top (**while**) or bottom (**do-while**).

```
for ( ;; ) {                  // infinite loop, while ( true )
    . . .
  if ( . . . ) break;         // middle exit
    . . .
}
```

- Exit condition *reversed* from **while** and *outdented* (eye-candy) for readability

- Eliminates priming (duplicated) code necessary with **while**.

`cin >> d; // priming`
`while ( ! cin.fail() ) {`
`    . . .`
`    cin >> d;`
`}`
	`for ( ;; ) {`
	`    cin >> d;`
	`  if ( cin.fail() ) break;`
	`    . . .`
	`}`

- Do not use multi-exit to simulate **while/for**, especially for loop index.

BAD	GOOD

`for ( int i = 0; ; i += 1 ) {`
`  if ( i == 10 ) break;`
`    S1`
`}`
	`for ( int i = 0; i < 10; i += 1 ) {`
	
	`    S1`
	`}`

- A loop exit **NEVER** needs an **else** clause.

BAD	GOOD	BAD	GOOD

`for ( ;; ) {`
`    S1`
`    if ( C1 ) {`
`        S2`
`    } else {`
`        break;`
`    }`
`    S3`
`}`
	`for ( ;; ) {`
	`    S1`
	`    if ( ! C1 ) break;`
	`    S2`
	
	`    S3`
	`}`
		`for ( ;; ) {`
		`    S1`
		`    if ( C1 ) {`
		`        break;`
		`    } else {`
		`        S2`
		`    }`
		`    S3`
		`}`
			`for ( ;; ) {`
			`    S1`
			`    if ( C1 ) break;`
			
			`    S2`
			
			`    S3`
			`}`

S2 is logically part of loop body ***not*** part of an **if**.

- Allow multiple exit conditions.

```
for ( ;; ) {
    S1
    if ( C1 ) { E1; break; }

    S2
    if ( C2 ) { E2; break; }

    S3
}
```

```
bool flag1 = false, flag2 = false;
while ( ! flag1 && ! flag2 ) {
    S1
    if ( C1 ) flag1 = true;
    } else {
        S2
        if ( C2 ) flag2 = true;
        } else {
            S3
        }
    }
}
if ( flag1 ) E1;
else E2;
```

- Eliminate **flag variables** used solely to affect control flow, i.e., variable does not contain data associated with computation.

- ***Flag variables are the variable equivalent to a goto*** because they can be set/reset/tested at arbitrary locations in a program.

1.1 Static multi-level exit

- **Static multi-level exit** exits multiple control structures where exit point is *known* at compile time.

- Labelled exit (**break/continue**) provides this capability.

μC++ / Java	C / C++

<pre>BK: { // good eye-candy
    ... declarations ...
    SW: switch (...) {
        FR: for (...) {
            ... break BK; ... // exit block
            ... break SW; ... // exit switch
            ... break FR; ... // exit loop
        }
        ...
    }
    ...
}</pre>
	<pre>{
	    ... declarations ...
	    switch (...) {
	        for (...) {
	            ... goto BK; ...
	            ... goto SW; ...
	            ... goto FR; ... // or break
	        } FR: ;
	        ...
	    } SW: ; // bad eye-candy
	    ...
	} BK: ;</pre>

- Why is it good practice to label all exits?
- Eliminate all flag variables with multi-level exit!

```
F1: for ( i = 0; i < 10; i += 1 ) {
    F2: for ( j = 0; j < 10; j += 1 ) {
            ...
        if ( ... ) break F2;  // outdent
            ... // rest of loop
    if ( ... ) break F1;  // outdent
            ... // rest of loop
    } // for
    ... // rest of loop
} // for
```

```
bool flag1 = false;
for ( i = 0; i < 10 && ! flag1; i += 1 ) {
    bool flag2 = false;
    for ( j = 0; j < 10 &&
            ! flag1 && ! flag2; j += 1 ) {
        ...
        if ( ... ) flag2 = true;
        else {
            ... // rest of loop
            if ( ... ) flag1 = true;
            else {
                ... // rest of loop
            } // if
        } // if
    } // for
    if ( ! flag1 ) {
        ... // rest of loop
    } // if
} // for
```

- **Occasionally a flag variable is necessary!**

```
// Retain state from one inner lexical (static) scope to another.
int val;   bool valDefault = false;
switch ( argv ) {
  ...
  case 3:
    if ( strcmp( argc[4], "d" ) ) valDefault = true; // default ?
    else val = stoi( argc[4] ); // value
  ...
} // switch
```

```
for ( ;; ) {
    . . .
    if ( valDefault ) // do something
    else // do another
    . . .
} // for
```

- Other uses of multi-level exit to remove duplicate code.

duplication	no duplication	

<pre>if (C1) {
    S1;
    if (C2) {
        S2;
        if (C3) {
            S3;
        } else
            S4;
    } else
        S4;
} else
    S4;</pre>
	<pre>C: {
	    if (C1) {
	        S1;
	        if (C2) {
	            S2;
	            if (C3) {
	                S3;
	  break C;
	            }
	        }
	    }
	    S4; // only once
	}</pre>
		<pre>{
		    if (C1) {
		        S1;
		        if (C2) {
		            S2;
		            if (C3) {
		                S3;
		                goto C;
		            }
		        }
		    }
		    S4; // only once
		} C: ;</pre>

- Normal and labelled **break** are a **goto** with limitations.
  1. Cannot loop (only forward branch) ⇒ only loop constructs branch back.
  2. Cannot branch ***into*** a control structure.
- **Only use goto to perform static multi-level exit, e.g., simulate labelled break and continue.**

1.2 Dynamic Memory Allocation

- Stack allocation eliminates explicit storage-management and is more efficient than heap allocation — **"Use the STACK, Luke Skywalker."**

```
{ // GOOD, use stack
    cin >> size;
    int arr[size]; // VLA, g++
    . . . // use arr[i]

}
```

```
{ // BAD, unnecessary dynamic allocation
    cin >> size;
    int * arr = new int[size];
    . . . // use arr[i]
    delete [] arr; // why "[ ]"?
}
```

- These are the situations where dynamic (heap) allocation is necessary.
  1. When storage must outlive the block in which it is allocated (ownership change).

```
Type * rtn(. . .) {
    Type * tp = new Type;    // MUST USE HEAP
    . . .                    // initialize/compute using tp
    return tp;               // storage outlives block
}                            // tp deleted later
```

  Similar to necessary flag variable: to retain state from a lower level.

2. When the amount of data read is unknown.

```
vector<int> input;
int temp;
for ( ;; ) {
    cin >> temp;
  if ( cin.fail() ) break;
    input.push_back( temp ); // implicit dynamic allocation
}
```

   Does switching to emplace_back help?

3. When an array of objects must be initialized via the object's constructor and each element has a different value.

```
struct Obj {
    const int id; ... // possibly other fields
    Obj( int id ) : id{ id } { ... }
};
ostream & operator<<( ostream & os, const Obj & obj ) {
   return os << obj.id;
}
// need to initialize each array element
Obj obj[10]; // no default constructor! declaration fails
for ( int id = 0; id < 10; id += 1 )
    obj[id].id = id; // Obj::id is const! assignment fails
```

   - Forced to use pointers and dynamic allocation.

```
Obj * objs[size];
for ( int id = 0; id < size; id += 1 )
    objs[id] = new Obj{ id };
...
for ( int id = 0; id < size; id += 1 )
    delete objs[id];
```

   - Two declaration/initialization alternatives: uArray and unique_ptr.

```
{ // GOOD, use stack
  cin >> size;
  uArray( Obj, objs, size ); // macro
  for ( int id = 0; id < size; id += 1 )
    objs[id]( id ); // constructor call
  ...
} // implicit array deallocate
```

```
{ // BAD, unnecessary dynamic allocation
  cin >> size;
  unique_ptr<Obj> objs[size];
  for ( int id = 0; id < size; id += 1 )
    objs[id] = make_unique<Obj>( id );
  ...
} // implicit array deallocate
```

   - Like unique_ptr, uArray allocates objs without element constructor calls (placement **new** allocation) **and it proves subscript checking**.
   - Subsequent calls to (...) or make_unique<T>(...) initialize array elements.
   - Allocation for uArray is $O(1)$ in stack, while unique_ptr is $O(N)$ in heap.
   - As for unique_ptr, use * for object and –> for field access.

```
for ( int id = 0; id < size; id += 1 )
    cout << *objs[id] << ' ' << objs[id]->id << endl;
```

   - Use uArray instead of unique_ptr or std::vector, which both use the heap.

4. When large local variables are allocated on a small stack.

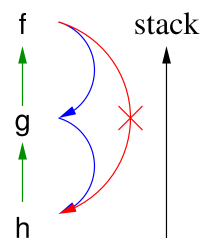
```
_Coroutine C {
    void main() {  // 64K stack
        Obj objs[100000]; // overflow
        // implicit initialize with ctor calls
        ...
    } // implicitly array deallocate
};
```

```
_Coroutine C {
    void main() {
        uArrayPtr( Obj, objs, 100000 )
        // explicit initialize with ctor calls
        ...
    } // implicitly array deallocate
};
```

- uArrayPtr dynamically allocates the array in the heap, and implicitly frees it at the end of the block (like unique_ptr).
- Alternatives are large stacks (waste virtual space) or dynamic stack growth (complex and pauses).

2 Nonlocal Transfer

- Routine **activation** (call/invocation) introduces complex control flow.
- ***Among*** routines, control flow is controlled by call/return mechanism.



  - routine h calls g calls f
  - cannot return from f to h, terminating g's activation

- **Modularization**: from software engineering, any contiguous code block can be factored into a (helper) routine and called in the program (modulo scoping rules).
- Modularization fails when refactoring exits, e.g., multi-level exits:

```
B1: for ( i = 0; i < 10; i += 1 ) {
      . . .
      B2: for ( j = 0; j < 10; j += 1 ) {
            . . .
            if ( . . . ) break B1;
            . . .
      }
      . . .
}
```

```
int rtn( ... ) {
      B2: for ( j = 0; j < 10; j += 1 ) {
            . . .
            if ( . . . ) break B1;
            . . .
      }
}
B1: for ( i = 0; i < 10; i += 1 ) {
      . . . w = rtn( ... ) . . .
}
```

Does this compile?

- Software pattern: many routines have **multiple outcomes**.
  - normal: return normal result and transfer after call
  - exceptional: return alternative result and **not** transfer after call
- **Nonlocal transfer** allows a routine to transfer back to its caller but **not** after the call.

```
C     Two alternate return parameters, denoted by * and implicitly named 1 and 2
      subroutine AltRet( c, *, * )
          integer c
          if ( c == 0 ) return          ! normal return
          if ( c == 1 ) return 1        ! alternate return
          if ( c == 2 ) return 2        ! alternate return
      end
```

```
C     Statements labelled 10 and 20 are alternate return points
      call AltRet( 0, *10, *20 )
      print *, "normal return 1"
      call AltRet( 1, *10, *20 )
      print *, "normal return 2"
      return
10    print *, "alternate return 1"
      call AltRet( 2, *10, *20 )
      print *, "normal return 3"
      return
20    print *, "alternate return 2"
      stop
      end
```

```
$ gfortran AltRtn.for
$ a.out
 normal return 1
 alternate return 1
 alternate return 2
```

- Generalization of multi-exit loop and multi-level exit.
  - Control structures ends normally or with an exceptional transfer.
- Pattern acknowledges:
  - algorithms can have multiple outcomes
  - separating outcomes makes it easy to read and maintain a program
- **Pattern does not handle multiple levels of nested modularization.**
- If AltRet is further modularized, new routine has an alternate return to AltRet, which retains its alternate return to its caller.

```
C     Two alternate return parameters, denoted by * and implicitly named 1 and 2
      subroutine AltRet2( c, *, * )
          integer c
          if ( c == 0 ) return        ! normal return
          if ( c == 1 ) return 1      ! alternate return
          return 2
      end
C     Two alternate return parameters, denoted by * and implicitly named 1 and 2
      subroutine AltRet( c, *, * )
          integer c
          call AltRet2( c, *30, *40 )
          return
30        return 1
40        if ( c == 2 ) return 2          ! alternate return
      end
```

- Why not call AltRet2(c, *10, *20)?

2.1 Traditional Approaches

- What are the traditional approaches for handling the multiple-outcome pattern?
- **return code**: returns value indicating normal or exceptional execution. e.g., printf() returns number of bytes transmitted or negative value.
- **status flag**: set shared (global) variable indicating normal or exceptional execution; the value remains as long as it is not overwritten. e.g., errno variable in UNIX.
- **fix-up routine**: a global and/or local routine called for an exceptional event to fix-up and return a corrective result so a computation can continue.

```
int fixup( int i, int j ) { . . . } // local routine
rtn( a, b, fixup ); // fixup called for exceptional event
```

  e.g., C++ has global routine-pointer new_handler called when **new** fails.

- Techniques are often combined, e.g.:

```
if ( printf(. . .) < 0 ) {        // check return code for error
    perror( "printf:");           // errno describes specific error
    abort();                      // terminate program
}
```

- **return union**: modern approach combining result/return-code and requiring return-code check on result access.
- **ALL** routines must return an appropriate union.

```
optional< int * > Malloc( size_t size ) {
    if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
    return nullopt;                         // no storage
}
optional< int > rtn( ) {
    optional< int * > p = Malloc( sizeof( int ) );
    if ( ! p ) return nullopt;              // malloc successful (true/false) ?
    **p = 7;        // compute
    if ( random() % 2 ) return **p;
    return nullopt;                         // bad computation
}
int main() {
    srandom( getpid() );
    optional< int > ret = rtn();
    if ( ret ) cout << *ret << endl;        // rtn successful?
    else cout << "no storage or bad computation" << endl;
}
$ repeat 5 a.out
no storage or bad computation
7
no storage or bad computation
7
7
```

```
enum Alloc { NoStorage };
variant< int *, Alloc > Malloc( size_t size ) {
    if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
    return NoStorage;
}
enum Comp { BadComp };
variant< int, Alloc, Comp > rtn( ) {
    variant< int *, Alloc > p = Malloc( sizeof( int ) );
    if ( ! holds_alternative<int *>(p) ) return NoStorage; // malloc successful ?
    *get<int *>(p) = 7;
    if ( random() % 2 ) return *get<int *>(p);
    return BadComp;
}

int main() {
    srandom( getpid() );
    variant< int, Alloc, Comp > ret = rtn();
    if ( holds_alternative<int>(ret) ) cout << get<int>(ret) << endl;
    else if ( holds_alternative<Comp>(ret) ) cout << "bad computation" << endl;
    else cout << "no storage" << endl;
}
$ repeat 5 a.out
no storage
bad computation
no storage
bad computation
7
```

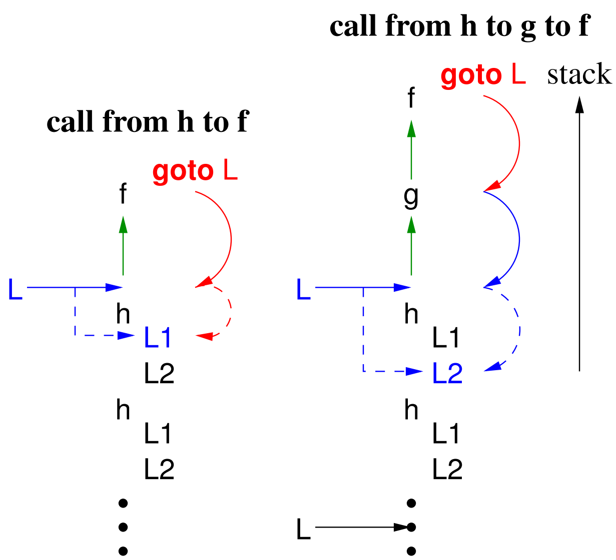
- Forces checking, unless explicitly access without holds_alternative.
- Like Fortran, only returns one level.
- Drawbacks of traditional techniques:
  - checking return code or status flag is optional ⇒ can be delayed or omitted, i.e., passive versus active
  - return code mixes exceptional and normal values ⇒ enlarges type or value range; normal/exceptional type/values should be independent
- Testing and handling of return code or status flag is often done locally (inline), otherwise information may be lost; but local testing/handling:
  - makes code difficult to read; each call results in multiple statements
  - can be inappropriate, e.g., library routines should **not terminate program**
- Nonlocal testing from nested routine calls is difficult as multiple codes are returned for analysis, compounding the mixing problem.
- Status flag can be overwritten before examined, and cannot be used in a concurrent environment because of sharing issues (e.g., save errno)

- Local fix-up routines increases the number of parameters.
  - increase cost of each call
  - must be passed through multiple levels enlarging parameter lists even when the fix-up routine is not used
- Nonlocal (global) fix-up routines, implemented with global routine pointer, have identical problems with status flags (e.g., new_handler).

2.2 Dynamic Multi-level Exit

- Rather than returning one level at a time, simpler for new modularized routine to bypass intermediate steps and transfer directly to original caller.
  - e.g., AltRet2 transfers directly to program main, instead of AltRet2 to AltRet to program main.
- **Dynamic multi-level exit** (DME) extend call/return semantics to transfer in the ***reverse*** direction to normal routine calls, requiring nonlocal transfer.

```
label L;
void f( int i ) {
    // nonlocal return
    if ( i == . . . ) goto L;
}
void g( int i ) {
    if ( i > 1 ) { g( i - 1 ); return; }
    f( i );
}
void h( int i ) {
    if ( i > 1 ) { h( i - 1 ); return; }
    L = L1; // set dynamic transfer-point
    f( 1 ); goto S1;
  L1: // handle L1 nonlocal return
  S1: // continue normal execution
    L = L2; // set dynamic transfer-point
    g( 1 ); goto S2;
  L2: // handle L2 nonlocal return
  S2: // continue normal execution
}
```



- **label variable** contains:
  1. pointer to a block activation on the stack;
  2. transfer point within the block.
- Nonlocal transfer, **goto** L, is a two-step operation.
  1. direct control flow to the specified activation on the stack;
  2. then go to the transfer point (label constant) within the routine.

- Therefore, a label value is not statically/lexically determined.
  - recursion in g ⇒ unknown distance between f and h on stack.
  - what if L is set during the recursion of h?
- This complexity is why label constants have local scope.
- ***Transfer between goto and label value causes termination of stack block.***
- First, nonlocal transfer from f transfers to the label L1 in h's routine activation, terminating f's activation.
- Second, nonlocal transfer from f transfers to the static label L2 in the stack frame for h, terminating the stack frame for f and g.
- Termination is implicit for direct transferring to h or requires stack unwinding if activations contain objects with destructors or finalizers.
- DME is possible in C using:
  - jmp_buf to declare a label variable,
  - setjmp to initialize a label variable,
  - longjmp to goto a label variable.
- DME allows multiple forms of returns to any level.
  - Normal return transfers to statement after the call, often implying completion of routine's algorithm.
  - Exceptional return transfers to statement **not** after the call, indicating an ancillary completion (but not necessarily an error).
- Unfortunately, nonlocal transfer is too general, allowing branching to almost anywhere, i.e., the goto problem.
- Simulate nonlocal transfer with return codes.

```
label L;
void f( int i, int j ) {

    for ( . . . ) {
        int k;
        . . .
  if ( i < j && k > i ) goto L;
        . . .
    }


}
void g( int i ) {

    for ( . . . ) {
        int j;
        . . . f( i, j ); . . .

    }


}
void h() {
    L = L1;
    for ( . . . ) {
        int i;
        . . . g( i ); . . .

    }
    . . .  return; // normal
    L1: . . . // exceptional
}
```

```
int f( int i, int j ) {
    bool flag = false;
    for ( ! flag && . . . ) {
        int k;
        . . .
  if ( i < j && k > i ) flag = true;
        else { . . . }
    }
    if ( ! flag ) { . . . }
    return flag ? -1 : 0;
}
int g( int i ) {
    bool flag = false;
    for ( ! flag && . . . ) {
        int j;
        . . . if ( f( i, j ) == -1 ) flag = true
        else { . . . }
    }
    if ( ! flag ) { . . . }
    return flag ? -1 : 0;
}
void h() {
    bool flag = false;
    for ( ! flag && . . . ) {
        int i;
        . . . if ( g( i ) == -1 ) flag = true;
        else { . . . }
    }
    if ( ! flag ) { . . . return; }
    . . .
}
```

2.3 Exception Handling

- DME, i.e., nonlocal transfer among routines, is often called **exception handling**.
- Exception handling is more than error handling.
- An **exceptional event** is an event that is (usually) known to exist but which is *ancillary* to an algorithm.
  - an exceptional event usually occurs with low frequency
  - e.g., division by zero, I/O failure, end of file, pop empty stack
- An **exception handling mechanism** (EHM) provides some or all of the alternate kinds of control-flow.
- Very difficult to simulate EHM with simpler control structures.
- Exceptions are supposed to make certain programming tasks easier, like robust programs.

- Robustness results because exceptions are active versus passive, forcing programs to react immediately when an exceptional event occurs.
- An EHM is not a panacea and only as good as the programmer using it.

2.4 Terminology

- **execution** is the language unit in which an exception can be raised, usually any entity with its own runtime stack.
- **exception type** is a type name representing an exceptional event.
- **exception** is an instance of an exception type, generated by executing an operation indicating an ancillary (exceptional) situation in execution.
- **raise** (**throw**) is the special operation that creates an exception.
- **source execution** is the execution raising an exception.
- **faulting execution** is the execution changing control flow due to a raised exception.
- **local exception** is when an exception is raised and handled by the same execution $\Rightarrow$ source = faulting.
- **nonlocal exception** is when an exception is raised by a source execution but **delivered** to a different faulting execution $\Rightarrow$ source $\neq$ faulting.
- **concurrent exception** is a nonlocal exception, where the source and faulting executions are executing concurrently.
- **propagation** directs control from a raise in the source execution to a handler in the faulting execution.
- **propagation mechanism** is the rules used to locate a handler.
  - most common propagation-mechanisms give precedence to handlers higher in the lexical/call stack
    - specificity versus generality
    - efficient linear search during propagation
- **handler** is inline (nested) routine responsible for handling raised exception.
  - handler **catch**es exception by **match**ing with one or more exception types
  - after catching, a handler executes like a normal subroutine
  - handler can return, reraise the current exception, or raise a new exception
  - **reraise** terminates current handling and continues propagation of caught exception.
    - useful if a handler cannot deal with an exception but needs to propagate same exception to handler further down the stack.

    * provided by a raise statement without an exception type:

      ```
      . . . throw;    // no exception type
      ```

      where a raise must be in progress.
  - an exception is **handled** only if the handler returns rather than reraises

- **guarded block** is a language block with associated handlers, e.g., try-block in C++/Java.
- **unguarded block** is a block with no handlers.
- **termination** means control cannot return to the raise point.
  - all blocks on the faulting stack from the raise block to the guarded block handling the exception are terminated, called **stack unwinding**
- **resumption** means control returns to the raise point ⇒ no stack unwinding.
- EHM = Exception Type + Raise (exception) + Propagation + Handlers

2.5 Execution Environment

- The execution environment has a significant effect on an EHM.
- An object-oriented concurrent environment requires a more complex EHM than a non-object-oriented sequential environment.
- E.g., objects may have destructors that must be executed no matter how the object ends, i.e., by normal or exceptional termination.

```
class T {
    int *i;
    T() { i = new int[10]; . . . }
    ~T() { delete [] i; . . . } // must free storage
};
L: {
    T t; // constructor must be executed
    . . . if ( . . . ) break L;
    . . .
} // destructor must be executed
```

- Control structures with **finally** clauses must always be executed (e.g., Java/μC++).

Java	μC++

`L: try {`
`    infile = new Scanner( new File( "abc" ) );`
`    . . . if ( . . . ) break L;`
`    . . .`
`} finally { // always executed`
`    infile.close(); // must close file`
 	
`}`
	`L: try {`
	`    infile = new ifstream( "abc" );`
	`    . . . if ( . . . ) break L; // alt 1`
	`    . . . // alt 2`
	`} _Finally { // always executed`
	`    infile.close();    // must close file`
	`    delete infile;     // deallocate`
	`}`

- Hence, terminating a block complicates the EHM as object destructors (and recursively for nested objects) and **finally** clauses must be executed.
- For C++, a direct nonlocal transfer is often impossible, because of local objects with destructors, requiring linear stack unwinding.
- Also, complex execution-environment involving continuation, coroutine, task, each with its own execution stack.
- Given multiple stacks, an EHM can be more sophisticated, resulting in more complexity.
  - e.g., if no handler is found in one stack, it is possible to continue propagating the exception in another stack.

2.6 Implementation

- DME is *limited* in most programming languages using exception handling.

```
struct E {};  // label
void f(...) {
    ...
    throw E(); // raise
    // control never returns here
}
int main() {
    try {
        f(...);
    } catch( E ) {...} // handler 1
    try {
        f(...);
    } catch( E ) {...} // handler 2
    ...
}
```

```
label L;
void f(...) {
    ...
    goto L;

}
int main() {
    L = L1; // set transfer-point
    f(...); goto S1;
  L1: // handle nonlocal return
  S1: L = L2; // set transfer-point
    f(...); goto S2;
  L2: // handle nonlocal return
  S2: ; ...
}
```

- To implement throw/catch, the throw must know the last guarded block with a handler for the raised exception type.
- One approach is to:
  - associate a label variable with each exception type
  - set label variable on entry to each guarded block with handler for the type
  - reset label variable on exit to previous value, i.e., previous guarded block for that type
- However, setting/resetting label variable on **try** block entry/exit has a cost (small).
  - rtn called million times but exception E never raised ⇒ million unnecessary operations.

```
void rtn( int i ) {
    try {                      // set label on entry
        ...
    } catch( E ) { ... }       // reset label on exit
}
```

- ○ Instead, **catch**/destructor data is stored once externally for each block and handler found by linear search during a stack walk (no direct transfer).
- ○ Advantage, millions of **try** entry/exit, but only tens of exceptions raised.

- Hence, termination is often implemented using zero cost on guarded-block entry but an expensive approach on raise.

2.7 Static/Dynamic Call/Return

- All routine/exceptional control-flow can be characterized by two properties:

1. static/dynamic call: routine/exception name at the call/raise is looked up statically (compile-time) or dynamically (runtime).
2. static/dynamic return: after a routine/handler completes, it returns to its static (definition) or dynamic (call) context.

return/handled	call/raise	
	static	dynamic
static	1) sequel	3) termination exception
dynamic	2) routine	4) routine pointer, virtual routine, resumption

- E.g., case 2) is a normal routine, with static name lookup at the call and a dynamic return.

2.8 Static Propagation (Sequel)

- Case 1) is called a **sequel**, which is a routine with no return value, where:
  - ○ the sequel name is looked up lexically at the call site, but
  - ○ control returns to the end of the block in which the sequel is declared.

```
A: for ( ;; ) {



    B: for ( ;; ) {

        C: for ( ;; ) {
            . . .
            if ( . . . ) { break A; }
            . . .
            if ( . . . ) { break B; }
            . . .
            if ( . . . ) { break C; }
            . . .
        }
    }
}
```

```
for ( ;; ) {
    sequel S1( . . . ) { . . . } // nested
    void M1( . . . ) {
        . . . if ( . . . ) S1( . . . ); . . .
    }
    for ( ;; ) {
        sequel S2( . . . ) { . . . } // nested
        C: for ( ;; ) {

            M1( . . . ); // modularize

            if ( . . . ) S2( . . . ); // modularize
            . . .
            if ( . . . ) break C;
            . . .
        }
    } // S2 static return
} // S1 static return
```

- Without a sequel, it is impossible to modularize code with static exits.
- ⇒ propagation is along the lexical structure
- Adheres to the termination model, as the stack is unwound.
- Sequel handles termination for a *non-recoverable* event (simple exception handling).

```
{ // new block
    sequel StackOverflow(...) { ... } // handler
    class stack {
        void push( int i ) {
            if (...) StackOverflow(...); // 2nd outcome
        } // 1st outcome
        ...
    };
    stack s;
    ... s.push( 3 ); ... // overflow ?
} // sequel returns here
```

- The advantage of the sequel is the handler is statically known (like static multi-level exit), and can be as efficient as a direct transfer.
- The disadvantage is that the sequel only works for monolithic programs because it must be statically nested at the point of use.
  - Fails for modular (library) code as the static context of the module and user code are disjoint.
  - E.g., if stack is separately compiled, the sequel call in push no longer knows the static blocks containing calls to it.

2.9 Dynamic Propagation

- Cases 3) and 4) are called termination and resumption, and both have dynamic raise with static/dynamic return, respectively.
- Dynamic propagation/static return (case 3) is also called dynamic multi-level exit (see Section 2.2, p. 11).
- The advantage is that dynamic propagation works for separately-compiled programs.
- The disadvantage (advantage) of dynamic propagation is the handler is not statically known.
  - without dynamic handler selection, the same action and context for that action is executed for every exceptional change in control flow.

2.9.1 Termination

- For termination:
  - control transfers from the start of propagation to a handler ⇒ dynamic raise (call)
  - when handler returns, it performs a static return ⇒ stack is unwound (like sequel)
- There are 2 basic termination forms for a *non-recoverable* operation: terminate and retry.
- **terminate** provides *limited* mechanism for block transfer on the call stack, like labelled **break**.

```
struct E {}; // label
void f(...) {
    ...
    throw E(); // raise
    // control never returns here
}
int main() {
    try {
        f(...);
    } catch( E ) {...} // handler 1
    try {
        f(...);
    } catch( E ) {...} // handler 2
    ...
}
```

- No intermediate code to forward alternative outcome (see return union examples page 9).

```
struct NoStorage {};
struct BadComp {};
int * Malloc( size_t size ) {
    if ( random() % 2 ) return (int *)malloc( sizeof( int ) );
    throw NoStorage();
}
int rtn( ) {
    int * p = Malloc( sizeof( int ) );
    // DO NOT HAVE TO FORWARD NoStorage
    *p = 7; // compute
    if ( random() % 2 ) return *p;
    throw BadComp();
}
int main() {
    srandom( getpid() );
    try { cout << rtn() << endl; }
    catch( BadComp ) { cout << "bad computation" << endl; }
    catch( NoStorage ) { cout << "no storage" << endl; }
}
```

- C++ I/O can be toggled to raise exceptions versus return codes (like μC++).

C++	μC++
`ifstream infile;`	`ifstream infile;`
`ofstream outfile;`	`ofstream outfile;`
`outfile.exceptions( ios_base::failbit );`	
`infile.exceptions( ios_base::failbit );`	
`switch ( argc ) {`	`switch ( argc ) {`
`  case 3:`	`  case 3:`
`    try {`	`    try {`
`        outfile.open( argv[2] );`	`        outfile.open( argv[2] );`
`    } catch( ios_base::failure & ) {...}`	`    } catch( uFile::Failure & ) {...}`
`    // fall through to handle input file`	`    // fall through to handle input file`
`  case 2:`	`  case 2:`
`    try {`	`    try {`
`        infile.open( argv[1] );`	`        infile.open( argv[1] );`
`    } catch( ios_base::failure & ) {...}`	`    } catch( uFile::Failure & ) {...}`
`    break;`	`    break;`
`  default:`	`  default:`
`    ...`	`    ...`
`} // switch`	`} // switch`
`string line;`	`string line;`
`try {`	
`    for ( ;; ) {  // loop until end-of-file`	`for ( ;; ) {`
`        getline( infile, line );`	`    getline( infile, line );`
`        outfile << line << endl;`	`  if ( infile.fail() ) break; // no eof exception`
`    }`	`    outfile << line << endl;`
`} catch ( ios_base::failure & ) {}`	`}`

- ios::exception mask indicates stream state-flags throw an exception if set
- failure exception raised after failed open or end-of-file when failbit set in exception mask
- μC++ provides exceptions for I/O errors, but no exception for eof.
- μC++ also provides **bound catch clause**, where catch depends on the object raising exception.

```
_Exception E {};
struct Obj {
    void mem() { ... _Throw E{}; ... } // implicitly store 'this' into exception
};
int main() {
    Obj obj1, obj2;
    try {
        ... obj1.mem(); ... obj2.mem(); ... _Throw E{};
    } catch( obj1.E ) {                 // only handle E from obj1 exception
    } catch( obj2.E ) {                 // only handle E from obj2 exception
    } catch( E ) {                      // handle any E exception
    }
}
```

- Better separation of alternate outcomes without flag variables.

```
istream * infile = &cin;                        // default value
ostream * outfile = &cout;                      // default value
try {
     switch ( argc ) {
       case 3: case 2:
          // open input file first as output creates file
          infile = new ifstream();
          dynamic_cast<ifstream *>(infile)->open( argv[3] );
          if ( argc == 3 ) {
               outfile = new ofstream();
               dynamic_cast<ofstream *>(outfile)->open( argv[4] );
          } // if
          // FALL THROUGH
       case 1:                                  // defaults
          break;
       default:                                 // wrong number of options
          // error
     } // switch
} catch( *infile.uFile::Failure & ) {           // input open failed
     cerr << "Error! Could not open input file \"" << argv[3] << "\"" << endl;
     exit( EXIT_FAILURE );                      // TERMINATE
} catch( *outfile.uFile::Failure & ) {          // output open failed
     cerr << "Error! Could not open output file \"" << argv[4] << "\"" << endl;
     exit( EXIT_FAILURE );                      // TERMINATE
} // try
```

- Why separate declaration and open versus infile = **new** ifstream(argv[3])?
- Why is dynamic cast necessary for open?
- **retry** is a combination of termination with special handler semantics, i.e., restart the guarded block handling the exception (Eiffel). (Pretend end-of-file is an exception of type Eof.)

Retry

```
char readfiles( char *files[ ], int N ) {
     int i = 0, value;
     ifstream infile;
     infile.open( files[i] );

     try {
          ... infile >> value; ...
     } retry( Eof ) {
          i += 1;
          infile.close();
       if ( i == N ) goto Finished;
          infile.open( files[i] );
     }
  Finished: ;
}
```

Simulation

```
char readfiles( char *files[ ], int N ) {
     int i = 0, value;
     ifstream infile;
     infile.open( files[i] );
     while ( true ) {
          try {
               ... infile >> value; ...
          } catch( eof ) {
               i += 1;
               infile.close();
            if ( i == N ) break;
               infile.open( files[i] );
          }
     }
}
```

- Because retry can be easily simulated, it is seldom supported directly.

2.9.2 Resumption

- **resumption** provides a *limited* mechanism to generate new blocks on the call stack:
  - ○ control transfers from the start of propagation to a handler ⇒ dynamic raise (call)
  - ○ when handler returns, it is dynamic return ⇒ stack is NOT unwound (like routine)
- A resumption handler is a corrective action so a computation can continue.

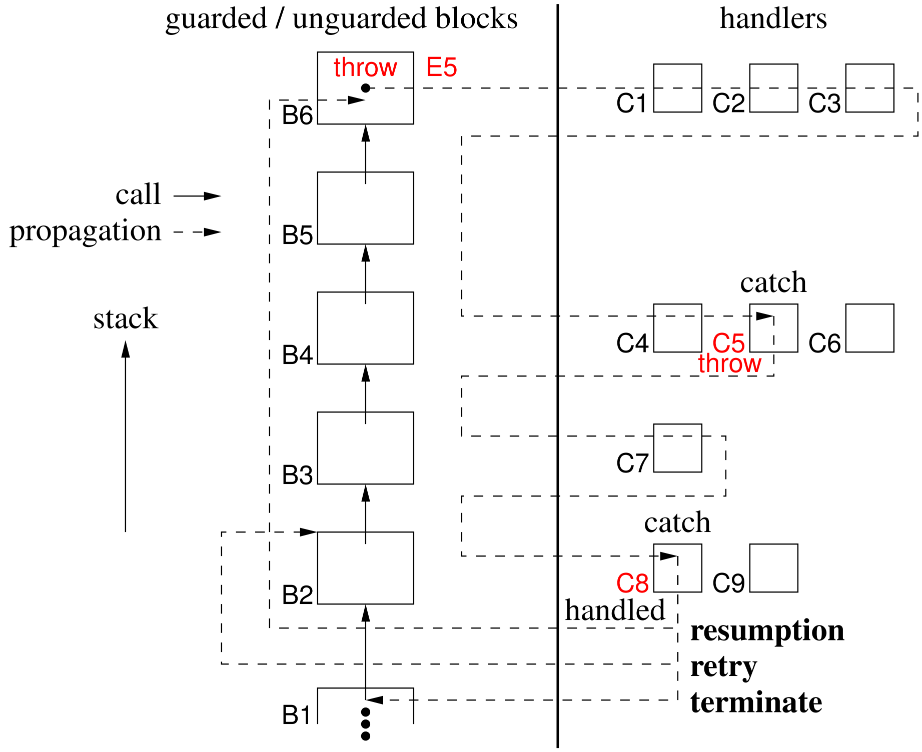
```
void f() {
    resume E(); // raise
    // control returns here
}
int main() {
    try {
        f(); // no parameters
    } catch( E ) {
        // handler 1
    }
    try {
        f(); // no parameters
    } catch( E ) {
        // handler 2
    }
}
```

```
void f( void (*fixup)() ) {
    fixup();
    // control returns here
}
void fixup1() {
    // handler 1
}
void fixup2() {
    // handler 2
}
int main() {
    f( fixup1 ); // parameters
    f( fixup2 ); // parameters
}
```

- No intermediate code to forward fixup down to raise point.

2.10 Exceptional Example

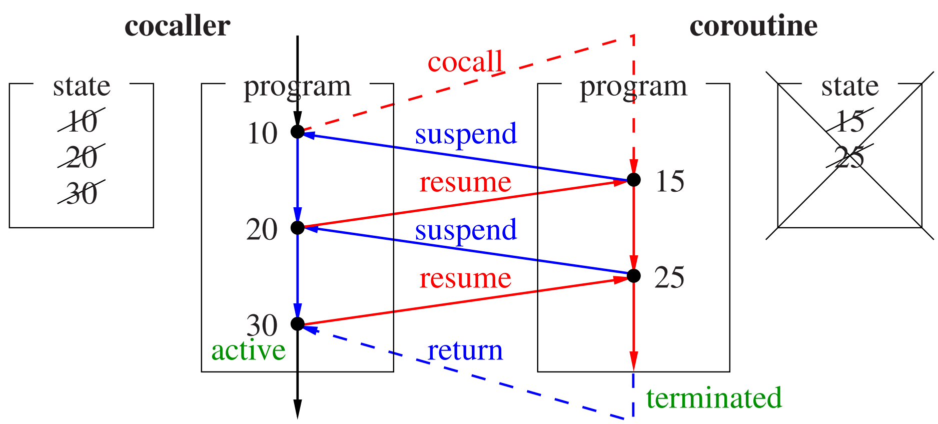
```
B1  {
B2      try {
B3          try {
B4              try {
B5                  {
B6                      try {
                            ... throw E5(); ...
C1                      } catch( E7 ) { ... }
C2                        catch( E8 ) { ... }
C3                        catch( E9 ) { ... }
                    }
C4              } catch( E4 ) { ... }
C5                catch( E5 ) { ... throw; ... }
C6                catch( E6 ) { ... }
C7          } catch( E3 ) { ... }
C8      } catch( E5 ) { ... resume/retry/terminate }
C9        catch( E2 ) { ... }
    }
```



guarded / unguarded blocks
handlers
throw
E5
B6
C1
C2
C3
call
propagation
B5
stack
catch
B4
C4
C5
throw
C6
B3
C7
catch
B2
C8
C9
handled
resumption
retry
terminate
B1

3 Coroutine

- A **coroutine** is a routine that can also be suspended at some point and resumed from that point when control returns.
- The state of a coroutine consists of:
  - an **execution location**, starting at the beginning of the coroutine and remembered at each suspend.
  - an **execution state** holding the data created by the code the coroutine is executing. ⇒ each coroutine has its own stack, containing its local variables and those of any routines it calls.
  - an **execution status**—**active** or **inactive** or **terminated**—which changes as control resumes and suspends in a coroutine.
- Hence, a coroutine does not start from the beginning on each activation; it is activated at the point of last suspension.
- In contrast, a routine always starts execution at the beginning and its local variables only persist for a single activation.



- A coroutine handles the class of problems that need to retain state between calls (e.g. plugin, device driver, finite-state machine).
- A coroutine executes synchronously with other coroutines; hence, no concurrency among coroutines.
- Coroutines are the precursor to concurrent tasks, and introduce the complex concept of suspending and resuming on separate stacks.
- Two different approaches are possible for activating another coroutine:
  1. A **semi-coroutine** acts asymmetrically, like non-recursive routines, by implicitly reactivating the coroutine that previously activated it.

2. A **full coroutine** acts symmetrically, like recursive routines, by explicitly activating a member of another coroutine, which directly or indirectly reactivates the original coroutine (activation cycle).

- These approaches accommodate two different styles of coroutine usage.

3.1 Semi-Coroutine

3.1.1 Fibonacci Sequence

$$f(n) = \begin{cases} 0 & n = 0 \\ 1 & n = 1 \\ f(n-1) + f(n-2) & n \geq 2 \end{cases}$$

- 3 states, producing unbounded sequence: 0, 1, 1, 2, 3, 5, 8, 13, 21, ...

3.1.1.1 Direct

- Compute and print Fibonacci numbers.

```
int main() {
    int fn, fn1, fn2;
    fn = 0;  fn1 = fn;                    // 1st case
    cout << fn << endl;
    fn = 1;  fn2 = fn1;  fn1 = fn;        // 2nd case
    cout << fn << endl;
    for ( ;; ) {                          // infinite loop
        fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn; // general case
        cout << fn << endl;
    }
}
```

- Convert to routine that generates a sequence of Fibonacci numbers on each call (no output):

```
int main() {
    for ( int i = 1; i <= 10; i += 1 ) { // first 10 Fibonacci numbers
        cout << fibonacci() << endl;
    }
}
```

- Examine different solutions.

3.1.1.2 Routine

```
int fn1, fn2, state = 1; // global variables
int fibonacci() {
    int fn;
    switch ( state ) {
      case 1:
        fn = 0;  fn1 = fn;  state = 2;
        break;
      case 2:
        fn = 1;  fn2 = fn1;  fn1 = fn;  state = 3;
        break;
      case 3:
        fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
        break;
    }
    return fn;
}
```

- unencapsulated global variables necessary to retain state between calls
- only one fibonacci generator can run at a time
- execution state must be explicitly retained

```
#define FIB_INIT { 0, 1 }          /* first two Fibonacci numbers */
struct Fibonacci { int fn2, fn1; };
int fib( Fibonacci & f ) {
    int ret = f.fn2;
    int fn = f.fn1 + f.fn2;        // only last state (3) in Fibonacci definition
    f.fn2 = f.fn1; f.fn1 = fn;
    return ret;
}
int main() {
    Fibonacci f1 = FIB_INIT, f2 = FIB_INIT;  // multiple instances
    for ( int i = 1; i <= 10; i += 1 ) {
        cout << fib( f1 ) << " " << fib( f2 ) << endl;
    }
}
```

- unencapsulated program global variables become encapsulated structure variables
- multiple fibonacci generators (objects) can run at a time
- execution state removed by precomputing first 2 Fibonacci numbers and returning $f(n-2)$

3.1.1.3 Class

```
class Fibonacci {
      int fn, fn1, fn2, state = 1; // global class variables
  public:
      int operator()() {          // functor
          switch ( state ) {
            case 1:
              fn = 0;  fn1 = fn;  state = 2;
              break;
            case 2:
              fn = 1;  fn2 = fn1;  fn1 = fn;  state = 3;
              break;
            case 3:
              fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
              break;
          }
          return fn;
      }
};
int main() {
      Fibonacci f1, f2;  // multiple instances
      for ( int i = 1; i <= 10; i += 1 ) {
          cout << f1() << " " << f2() << endl;
      } // for
}
```

- unencapsulated program global variables become encapsulated object global variables
- multiple fibonacci generators (objects) can run at a time
- execution state still explicit or use initialization trick

3.1.1.4 Coroutine

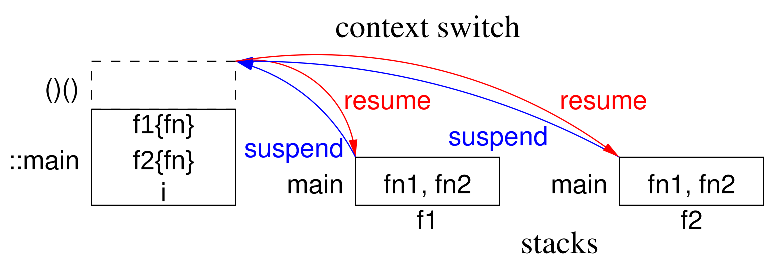
```
_Coroutine Fibonacci {    // : public uBaseCoroutine
      int fn;               // used for communication
      void main() {         // distinguished member
          int fn1, fn2;      // retained between resumes
          fn = 0;  fn1 = fn;
          suspend();         // return to last resume
          fn = 1;  fn2 = fn1;  fn1 = fn;
          suspend();         // return to last resume
          for ( ;; ) {
              fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
              suspend();     // return to last resume
          }
      }
  public:
      int operator()() {    // functor
          resume();          // transfer to last suspend
          return fn;
      }
};
```

```
int main() {
    Fibonacci f1, f2;        // multiple instances
    for ( int i = 1; i <= 10; i += 1 ) {
        cout << f1() << " " << f2() << endl;
    }
}
```

- **no explicit execution state!** (see direct solution)
- **_Coroutine** type wraps coroutine and provides *all* **class** properties
- distinguished member main (coroutine main) can be suspended and resumed
- no parameters or return value (supplied by **public** members and communication variables).
- coroutine main can be called (even recursively), but normally a **private/protected** member. Why?
- **compile with u++ command**
- All coroutines inherit from base type uBaseCoroutine:

```
class uBaseCoroutine {
  protected:
    void resume();                    // context switch to this
    void suspend();                   // context switch to last resumer
    virtual void main() = 0;          // starting routine for coroutine
  public:
    uBaseCoroutine();
    uBaseCoroutine( unsigned int stackSize ); // set stack size
    void verify();                    // check stack
    const char * setName( const char * name ); // printed in error messages
    const char * getName() const;
    uBaseCoroutine & starter() const; // coroutine performing first resume
    uBaseCoroutine & resumer() const; // coroutine performing last resume
};
```

- Program main called from hidden coroutine ⇒ **has coroutine properties**.
- resume/suspend cause a **context switch** between coroutine stacks



- first resume starts main on new stack (cocall); subsequent resumes reactivate last suspend.

- suspend reactivates last resume
- object becomes a coroutine on first resume; coroutine becomes an object when main ends
- routine frame at the top of the stack *knows* where to activate execution
- suspend/resume are **protected** members to prevent external calls. Why?
- Coroutine main does not have to return before a coroutine object is deleted.
- When deleted, a coroutine's stack is always unwound and any destructors executed. Why?
- **Warning, do not use catch(...) (catch any) in a coroutine, if it may be deleted before terminating, because a cleanup exception is raised to force stack unwinding (implementation issue).**

3.1.2 Format Output

Unstructured input:

```
abcdefghijklmnopqrstuvwxyzabcdefghijklmnopqrstuvwxyz
```

Structured output:

```
abcd  efgh  ijkl  mnop  qrst
uvwx  yzab  cdef  ghij  klmn
opqr  stuv  wxyz
```

blocks of 4 letters, separated by 2 spaces, grouped into lines of 5 blocks.

3.1.2.1 Direct

- Read characters and print formatted output.

```
int main() {
    int g, b;
    char ch;
    cin >> noskipws;                    // turn off white space skipping
    for ( ;; ) {                        // for as many characters
        for ( g = 0; g < 5; g += 1 ) {  // groups of 5 blocks
            for ( b = 0; b < 4; b += 1 ) { // blocks of 4 chars
                for ( ;; ) {            // for newline characters
                    cin >> ch;          // read one character
  if ( cin.fail() ) goto fini; // eof ? multi-level exit
                  if ( ch != '\n' ) break; // ignore newline
                }
                cout << ch;             // print character
            }
            cout << "  ";               // print block separator
        }
        cout << endl;                   // print group separator
    }
  fini: ;
    if ( g != 0 || b != 0 ) cout << endl; // special case
}
```

- Convert to routine passed one character at a time to generate structured output (no input).

3.1.2.2 Routine

```
int g, b;                          // global variables
void fmtLines( char ch ) {
    if ( ch != -1 ) {              // not EOF ?
        if ( ch == '\n' ) return; // ignore newline
        cout << ch;                // print character
        b += 1;
        if ( b == 4 ) {            // block of 4 chars
            cout << "  ";          // block separator
            b = 0;
            g += 1;
        }
        if ( g == 5 ) {            // group of 5 blocks
            cout << endl;          // group separator
            g = 0;
        }
    } else {
        if ( g != 0 || b != 0 ) cout << endl; // special case
    }
}
int main() {
    char ch;
    cin >> noskipws;               // turn off white space skipping
    for ( ;; ) {                   // for as many characters
        cin >> ch;
      if ( cin.fail() ) break;     // eof ?
        fmtLines( ch );
    }
    fmtLines( -1 );                // indicate EOF
}
```

- must retain variables b and g between successive calls.
- only one instance of formatter
- linearize (flatten) loops: one loop, lots of **if** statements

3.1.2.3 Class

```
class Format {
    int g, b;                      // global class variables
  public:
    Format() : g( 0 ), b( 0 ) {}
    ~Format() { if ( g != 0 || b != 0 ) cout << endl; }
    void prt( char ch ) {
      if ( ch == '\n' ) return;    // ignore newline
        cout << ch;                // print character
        b += 1;
```

```
            if ( b == 4 ) {               // block of 4 chars
                cout << "  ";             // block separator
                b = 0;
                g += 1;
            }
            if ( g == 5 ) {               // group of 5 blocks
                cout << endl;             // group separator
                g = 0;
            }
        }
};
int main() {
    Format fmt;
    char ch;
    cin >> noskipws;                      // turn off white space skipping
    for ( ;; ) {                          // for as many characters
        cin >> ch;                        // read one character
      if ( cin.fail() ) break;            // eof ?
        fmt.prt( ch );
    }
}
```

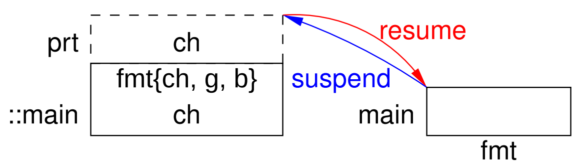
- Solves encapsulation and multiple instances issues, but explicitly managing execution state.

3.1.2.4 Coroutine

```
_Coroutine Format {
    char ch;                              // used for communication
    int g, b;                             // global because used in destructor
    void main() {
        for ( ;; ) {                      // for as many characters
            for ( g = 0; g < 5; g += 1 ) { // groups of 5 blocks
                for ( b = 0; b < 4; b += 1 ) { // blocks of 4 characters
                    for ( ;; ) {          // for newline characters
                        suspend();
                      if ( ch != '\n' ) break; // ignore newline
                    }
                    cout << ch;           // print character
                }
                cout << "  ";             // print block separator
            }
            cout << endl;                 // print group separator
        }
    }
  public:
    Format() { resume(); }                // start coroutine
    ~Format() { if ( g != 0 || b != 0 ) cout << endl; }
    void prt( char ch ) { Format::ch = ch; resume(); }
};
```

```
int main() {
    Format fmt;
    char ch;
    cin >> noskipws;            // turn off white space skipping
    for ( ;; ) {
        cin >> ch;              // read one character
      if ( cin.fail() ) break;  // eof ?
        fmt.prt( ch );
    }
}
```

- resume in constructor allows coroutine main to get to 1st input suspend.



3.1.3 Correct Coroutine Usage

- **Eliminate computation or flag variables retaining information about execution state.**
- E.g., sum even and odd digits of 10-digit number, where each digit is passed to coroutine:

BAD: Explicit Execution State	GOOD: Implicit Execution State

`for ( int i = 0; i < 10; i += 1 ) {`
`    if ( i % 2 == 0 ) // even ?`
`        even += digit;`
`    else`
`        odd += digit;`
`    suspend();`
`}`
	`for ( int i = 0; i < 5; i += 1 ) {`
	
	`    even += digit;`
	`    suspend();`
	`    odd += digit;`
	`    suspend();`
	`}`

- Right example illustrates coroutine “Zen”; let it do the work.
- E.g., a BAD solution for the previous Fibonacci generator is:

```
void main() {
    int fn1, fn2, state = 1;
    for ( ;; ) {
        switch (state) {            // no Zen
          case 1:
            fn = 0;  fn1 = fn;
            state = 2;
            break;
          case 2:
            fn = 1;  fn2 = fn1;  fn1 = fn;
            state = 3;
            break;
          case 3:
            fn = fn1 + fn2;  fn2 = fn1;  fn1 = fn;
            break;
        }
        suspend();                  // no Zen
    }
}
```

- Coroutine's capabilities not used:
  - explicit flag variable controls execution state
  - original program structure lost in **switch** statement
- Must do more than just *activate* coroutine main to demonstrate understanding of retaining data and execution state within a coroutine.

3.1.4 Coroutine Construction

- Fibonacci and formatter coroutines express original algorithm structure (no restructuring).
- When possible, simplest coroutine construction is to write a direct (stand-alone) program.
- Convert to coroutine by:
  - putting processing code into coroutine main,
  - converting reads if program is consuming or writes if program is producing to suspend,
    - Fibonacci consumes nothing and produces (generates) Fibonacci numbers ⇒ convert writes (cout) to suspends.
    - Formatter consumes characters and only indirectly produces output (as side-effect) ⇒ convert reads (cin) to suspends.
  - use interface members and communication variables to transfer data in/out of coroutine.
- This approach is impossible for advanced coroutine problems.

3.2 μC++ EHM

The following features characterize the μC++ EHM:

- exceptions must be generated from a specific kind of type.
- supports two kinds of raising: throw and resuming.
- supports two kinds of handlers, termination and resumption, matching with the kind of raise.
- supports propagation of nonlocal and concurrent exceptions.
- all exception types (user, runtime, and I/O) are grouped into a hierarchy.

3.3 Exception Type

- C++ allows any type to be used as an exception type.
- μC++ restricts exception types to those types defined by **_Exception**.

```
_Exception exception-type-name { . . . };
```

- An exception type has all the properties of a **class**.
- Every exception type must have a public default and copy constructor.
- An exception is the same as a class-object with respect to creation and destruction.

```
_Exception D { . . . };
D d;                    // local creation
_Resume d;
D *dp = new D;          // dynamic creation
_Resume *dp;
delete dp;
_Throw D();             // temporary local creation
```

3.4 Inherited Members

- Each exception type inherits the following members from uBaseEvent:

```
class uBaseEvent {  // like std::exception
    uBaseEvent( const char *const msg = "" );
    const char *const message() const;
    const uBaseCoroutine &source() const;
    const char *sourceName() const;
    virtual void defaultTerminate();
    virtual void defaultResume();
};
```

- uBaseEvent(**const char** *const msg = "") – msg is printed if the exception is not caught.

  ◦ Message string is copied so it is safe to use within an exception even if the context of the raise is deleted.

- message returns the string message associated with an exception.
- source returns the coroutine/task that raised the exception.
  ◦ coroutine/task may be deleted when the exception is caught so this reference may be undefined.
- sourceName returns the name of the coroutine/task that raised the exception.
  ◦ name is copied from the raising coroutine/task when exception is created.
- defaultTerminate is implicitly called if an exception is thrown but not handled.
  ◦ default action is to forward an UnhandledException exception to resumer/joiner.
- defaultResume is implicitly called if an exception is resumed but not handled.
  ◦ default action is to throw the exception.

3.5 Raising

- There are two raising mechanisms: throwing and resuming.

```
_Throw [ exception-type ] ;
_Resume [ exception-type ] [ _At uBaseCoroutine-id ] ;
```

- If **_Throw** has no *exception-type*, it is a rethrow.
- If **_Resume** has no *exception-type*, it is a reresume.
- The optional **_At** clause allows the specified exception or the currently propagating exception to be raised at another coroutine or task.
- Nonlocal/concurrent raise restricted to resumption as raising execution-state is often unaware of the handling execution-state.
- Resumption allows faulting execution greatest flexibility: it can process the exception as a resumption or rethrow the exception for termination.
- Exceptions in μC++ are propagated differently from C++.

<table>
<tr><th>C++</th><th>μC++</th></tr>
<tr><td><pre>class B {};
class D : public B {};
void f(B & t) { . . . throw t; . . . }
try {
    D m;
    f(m);
} catch (D &) { cout << "D" << endl; }
  catch (B &) { cout << "B" << endl; }</pre></td><td><pre>_Exception B {};
_Exception D : public B {};
void f(B & t) { . . . _Throw t; . . .}
try {
    D m;
    f(m);
} catch (D &) { cout << "D" << endl; }
  catch (B &) { cout << "B" << endl; }</pre></td></tr>
</table>

- In C++, routine f is passed an object of derived type D but throws an object of base type B.
- In μC++, routine f is passed an object of derived type D and throws the original object of type D.
- This change allows handlers to catch the specific (derived) rather than the general (base) exception-type.

3.6 Handler

- μC++ has two kinds of handlers, termination and resumption, which match with the kind of raise.

3.6.1 Termination

- The μC++ termination handler is the **catch** clause of a **try** block, i.e., same as in C++.

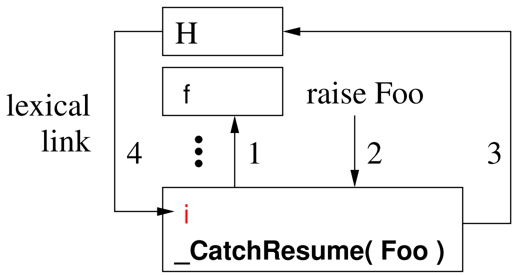
3.6.2 Resumption

- μC++ extends the **try** block to include resumption handlers.
- Resumption handler is denoted by a **_CatchResume** clause after **try** body:

```
try {
    ...
}   _CatchResume( E1 ) { ... }  // must appear before catch clauses
    // more _CatchResume clauses
    _CatchResume( ... ) { ... } // must be last _CatchResume clause
    catch( E2 ) { ... }          // must appear after _CatchResume clauses
    // more catch clauses
    catch( ... ) { ... }         // must be last catch clause
```

- Any number of resumption handlers can be associated with a **try** block.
- All **_CatchResume** handlers must precede any **catch** handlers, solely to make reading the two sets of clauses easier.
- Like **catch**(...) (catch-any), **_CatchResume**(...) must appear at the end of the list of the resumption handlers.
- Resumption handler can access types and variables visible in its local scope.

```
typedef int Foo;
Foo i;
try {
    f(...)                  // f is recursive and raises Foo
} _CatchResume( Foo & e ) { // handler H
    Foo fix = i;            // use type and variable in local scope
    ... e = fix ...         // change _Resume block
}
```



1. call f
2. propagation from f to handler H
3. call handler
4. dereference lexical link to i

- **lexical link** is like **this** but to declaration block rather than object.
- *Resumption handler cannot perform a* **break**, **continue**, **goto**, *or* **return**.
  - Resumption handler is corrective action so computation can continue.
  - If correction impossible, handler should **throw** an exception not step into an enclosing block to cause the stack to unwind.

```
B: try {
       f();                    // recursive calls and _Resume E()
} _CatchResume( E e ) { // handler H
       ... break B;            // force static return (disallowed)
       _Throw e;               // force recovery (allowed)
}
```

  - Handler H above makes recursive calls to f, so **goto** must unwind stack to transfer into stack frame B (nonlocal transfer).
  - Throw may find another recovery action closer to raise point than B that can deal with the problem.

3.6.3 Termination/Resumption

- The raise dictates set of handlers examined during propagation:
  - terminating propagation (**_Throw**) only examines termination handlers (**catch**),
  - resuming propagation (**_Resume**) only examines resumption handlers (**_CatchResume**).
- Exception types in each set can overlap.

```
_Exception E {};
void rtn() {
     try {
          _Resume E();
     } _CatchResume( E & e ) { ... _Throw e; }    // H1
       catch( E & e ) { ... }                       // H2
}
```

- Resumption handler H1 is invoked by the resume in the **try** block generating call stack:

  rtn → **try**{}**_CatchResume(E)**, **catch**(E)→ H1

- Handler H1 throws E and the stack is unwound until the exception is caught by termination-handler **catch**(E) and handler H2 is invoked.

  rtn → H2

- The termination handler is available as resuming does not unwind the stack.

- Note interaction between resuming, defaultResume, and throwing:

```
_Exception R {};
void rtn() {
    try {
        _Resume R();           // resume not throw
    } catch( R & ) { . . . }   // H1, no _CatchResume!!!
}
```

- This generates the following call stack as there is no eligible resumption handler (or there is a handler but marked ineligible):

  rtn → **try**{}**catch(R)** → defaultResume

- ***When* defaultResume *is called, the default action throws* R** (see Section 3.4, p. 35).

  rtn → H1

- Terminating propagation unwinds the stack until there is a match with the **catch** clause in the **try** block.

3.6.4 Object Binding

- **_Resume** / **_Throw** implicitly store the **this** associated with the member raising an exception.

- For a static member or free routine, there is no binding (no **this**).

- For non-local raise, the binding is the coroutine/task executing the raise.

3.6.5 Bound Handlers

- **catch** / **_CatchResume** provide object-specific matching.

  catch(***raising-object* .** *exception-declaration*) { . . . }
  _CatchResume(***raising-object* .** *exception-declaration*) { . . . }

- The "catch-any" handler, ". . .", does not have a bound form.

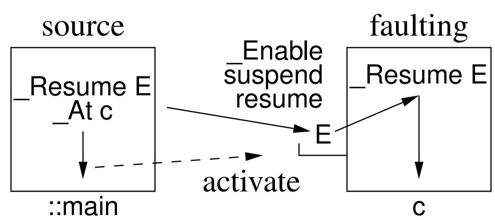
- An exception is caught when the bound and handler objects are equal, and the raised exception equals the handler exception or its base-type.

3.7 Nonlocal Exceptions

- Nonlocal exceptions are exceptions raised by a source execution at a faulting execution.
- Nonlocal exceptions are possible because each coroutine (execution) has its own stack.
- Nonlocal exceptions are raised using **_Resume** ... **_At** ....

```
_Exception E {};
_Coroutine C {
    void main() {
        // initialization, no nonlocal delivery
        try {                   // setup handlers
            _Enable {           // allow nonlocal exceptions
                ... suspend(); ... // inside suspend is _Resume E();
            }                   // disable all nonlocal exceptions
        } _CatchResume( E ) { ... // option 1: continue after suspend
        } _catch( E ) { ... // option 2: continue after try
        }
        // finalization, no nonlocal delivery
    }
  public:
    C() { resume(); }           // prime try (not always possible)
    void mem() { resume(); }
};
int main() {
    C c;
    _Resume E() _At c;          // exception pending
    c.mem();                    // trigger exception
}
```

- For nonlocal resumption, **_Resume** is a *proxy* for actual raise in the faulting coroutine ⇒ **non-local resumption becomes local resumption**.



- While source delivers nonlocal exception immediately, propagation only occurs when faulting becomes active.

  ⇒ must suspend back to or call a member that does a resume of the faulting coroutine
- Faulting coroutine performs local **_Resume** implicitly at detection points for nonlocal exceptions, e.g., in **_Enable**, suspend, resume.
- Handler does not return to the proxy raise; control returns to the implicit local raise at exception delivery, e.g., back in **_Enable**, suspend, resume.

- Multiple nonlocal exceptions are queued and delivered in FIFO order depending on the current enabled exceptions.

- **Nonlocal delivery is initially disabled for a coroutine**, so handlers can be set up before any exception can be delivered (also see Section 5.11, p. 81).

- Hence, nonlocal exceptions must be explicitly enabled before delivery can occur with **_Enable**.

- μC++ allows dynamic enabling and disabling of individual exception types versus all exception types.

```
_Enable <E1><E2>... {                  _Disable <E1><E2>... {
    // exceptions E1, E2 enabled           // exceptions E1, E2 disabled
}                                      }
```

- No exceptions is shorthand for specifying all nonlocal exceptions.

- Nested **_Enable** *or* **_Disable** blocks are additive ⇒ set of enabled or disabled exceptions increases on entry and decreases on exit.

```
_Enable <E> { // E enabled                _Disable <E> { // E disabled
    _Enable <F> // E & F enabled              _Disable <F> // E & F disabled
        _Enable { // all except. enabled          _Disable { // all except. disabled
        } //  E & F enabled                        } //  E & F disabled
    } //  E enabled                            } //  E disabled
}                                         }
```

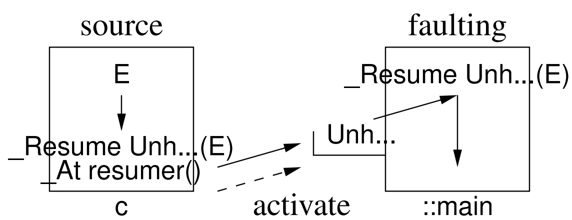
- Nested **_Enable** *and* **_Disable** blocks are subtractive ⇒ set of enabled or disabled exceptions decreases on entry and increases on exit.

```
_Enable <E> { //  E enabled                _Disable <E> { //  E disabled
    _Disable <E> { //  E disabled              _Enable <E> { //  E enabled
        _Disable { // all except. disabled         _Enable { // all except. enabled
        } //  E disabled                            } //  E enabled
    } //  E enabled                             } //  E disabled
}                                          }
```

- An unhandled exception in a coroutine raises a nonlocal exception of type uBaseCoroutine::-UnhandledException at the coroutine's ***last resumer*** and then terminates the coroutine.

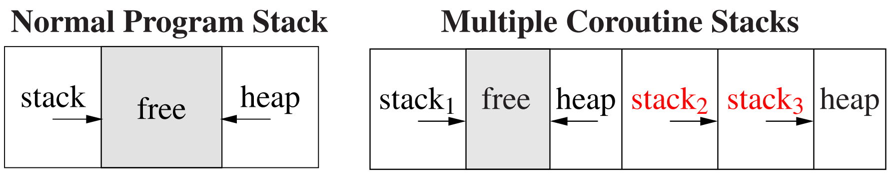
```
_Exception E {};
_Coroutine C {
      void main() { _Throw E(); } // unwind
      // defaultTerminate ⇒ _Resume UnhandledException() _At resumer()
      // ⇒ coroutine activates last resumer (not starter) and terminates
   public:
      void mem() { resume(); } // inside resume is _Resume UnhandledException()
};
int main() {
      C c;
      try { c.mem(); // resume coroutine
      } _CatchResume( uBaseCoroutine::Unh... & ) { ... // option 1: continue after resume
      } catch( uBaseCoroutine::Unh... & ) { ... // option 2: continue after try
      }
}
```

- Call to c.mem resumes coroutine c and then coroutine c throws exception E but does not handle it.
- When the base of c's stack is reached, an exception of type uBaseCoroutine::UnhandledException is raised at ::main, since it last resumed c.



- **_CatchResume** continues from resume (dynamic return, fixup)
- **catch** continues after handler (static return, recover)
- Forwarding can occur across any number of coroutines, until a task main forwards and then the program terminates by calling main's set_terminate.
- The original E exception is in the UnhandledException exception and can be thrown by uh.triggerCause().
- *If the original (*E*) exception has a default-terminate routine, it can override* UnhandledException *behaviour (e.g.,* abort*), or return and let it happen.*
- *While the coroutine terminates, control returns to its last resumer rather than its starter.*
- *Exception* UnhandledException *(and a few others) are always enabled.*

3.8 Memory Management



- Normally program stack expands to heap; but coroutine stacks expand to next stack.
- In fact, coroutine stacks are normally allocated in the heap.
- Default μC++ coroutine stack size is 256K **and it does not grow**.
- Adjust initial coroutine stack-size through coroutine constructor:

```
_Coroutine C {
  public:
    C() : uBaseCoroutine( 8192 ) {};      // default 8K stack
    C( int size ) : uBaseCoroutine( size ) {};  // user specified stack size
    . . .
};
C x, y( 16384 );        // x has an 8K stack, y has a 16K stack
```

- Check for stack overflow using coroutine member verify:

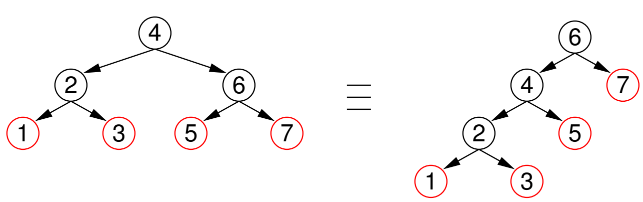
```
void main() {
    . . .          // declarations
    verify();      // check for stack overflow
    . . .          // code
}
```

- Be careful allocating arrays in the coroutine main; sometimes necessary to allocate large arrays in heap. (see Point 4, p. 6)

3.9 Semi-Coroutine Examples

3.9.1 Same Fringe

- Two binary trees have same fringe if all leafs are equals from left to right.



- Requires iterator to traverse a tree, return the value of each leaf, and continue the traversal.
- *No direct solution without additional data-structure (e.g., stack) to manage tree traversal.*

- Coroutine uses recursive tree-traversal but suspends during traversal to return value.

```
template< typename T > class Btree {
    struct Node { ... }; ... // other members
  public:
    _Coroutine Iterator {
        Node * cursor;
        void walk( Node * node ) {    // walk tree
          if ( node == nullptr ) return;
            if ( node->left == nullptr && node->right == nullptr ) { // leaf?
                cursor = node;
                suspend();            // multiple stack frames
            } else {
                walk( node->left );   // recursion
                walk( node->right );  // recursion
            }
        }
        void main() { walk( cursor ); cursor = nullptr; }

      public:
        Iterator( Btree<T> & btree ) : cursor( &btree.root ) {}
        T * next() {
            resume();
            return cursor;
        }
    };
    ... // other members
};

template<class T> bool sameFringe( BTree<T> & tree1, BTree<T> & tree2 ) {
    Btree<T>::Iterator iter1( btree1 ), iter2( btree2 ); // iterator for each tree
    T * t1, * t2;
    for ( ;; ) {
        t1 = iter1.next(); t2 = iter2.next();
      if ( t1 == nullptr || t2 == nullptr ) break; // one traversal complete ?
  if ( *t1 != *t2 ) return false; // elements not equal ?
    }
    return t1 == nullptr && t2 == nullptr; // both traversals completed ?
}
```

3.9.2 Device Driver

- Parse transmission protocol and return message text, e.g.:

  ...**STX** ...message ...**ESC ETX** ...message ...**ETX** 2-byte CRC ...

3.9.2.1 Direct

```
int main() {
    enum { STX = '\002', ESC = '\033', ETX = '\003' };
    enum { MaxMsgLnth = 64 };
    unsigned char msg[MaxMsgLnth];
    ...
```

```
    try {
      msg: for ( ;; ) {                      // parse messages
            int lnth = 0, checkval;
            do {
                byte = input( infile );      // read bytes, throw Eof on eof
            } while ( byte != STX );         // message start ?
          eom: for ( ;; ) {                  // scan message data
                byte = input( infile );
                switch ( byte ) {
                  case STX:
                     . . .                   // protocol error
                     continue msg;           // uC++ labelled continue
                  case ETX:                  // end of message
                     break eom;              // uC++ labelled break
                  case ESC:                  // escape next byte
                     byte = input( infile );
                     break;
                } // switch
                if ( lnth >= MaxMsgLnth ) { // buffer full ?
                     . . .                   // length error
                     continue msg;           // uC++ labelled continue
                } // if
                msg[lnth] = byte;            // store message
                lnth += 1;
            } // for
            byte = input( infile );          // gather check value
            checkval = byte;
            byte = input( infile );
            checkval = (checkval << 8) | byte;
            if ( ! crc( msg, lnth, checkval ) ) . . . // CRC error
        } // for
    } catch( Eof ) {}
    . . .
} // main
```

3.9.2.2 Coroutine

- Called by interrupt handler for each byte arriving at hardware serial port.

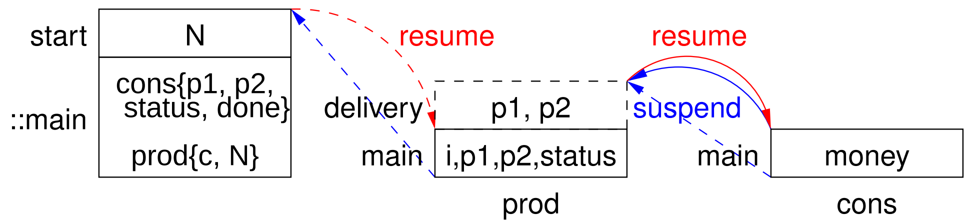
```
_Coroutine DeviceDriver {
    enum { STX = '\002', ESC = '\033', ETX = '\003' };
    enum { MaxMsgLnth = 64 };
    unsigned char byte;
    unsigned char * msg;
  public:
    DeviceDriver( unsigned char * msg ) : msg( msg ) { resume(); }
    void next( unsigned char b ) {           // called by interrupt handler
        byte = b;
        resume();
    }
```

```
  private:
    void main() {
      msg: for ( ;; ) {                     // parse messages
            int lnth = 0, checkval;
            do {
                suspend();
            } while ( byte != STX );        // message start ?
          eom: for ( ;; ) {                 // scan message data
                suspend();




                switch ( byte ) {
                  case STX:
                    . . .                   // protocol error
                    continue msg;           // uC++ labelled continue
                  case ETX:                 // end of message
                    break eom;              // uC++ labelled break
                  case ESC:                 // escape next byte
                    suspend();              // get escaped character
                    break;
                } // switch




                if ( lnth >= MaxMsgLnth ) { // buffer full ?
                    . . .                   // length error
                    continue msg;           // uC++ labelled continue
                } // if
                msg[lnth] = byte;           // store message
                lnth += 1;
            } // for




            suspend();                      // gather check value
            checkval = byte;
            suspend();
            checkval = (checkval << 8) | byte;
            if ( ! crc( msg, lnth, checkval ) ) . . . // CRC error
        } // for
    } // main
}; // DeviceDriver
```

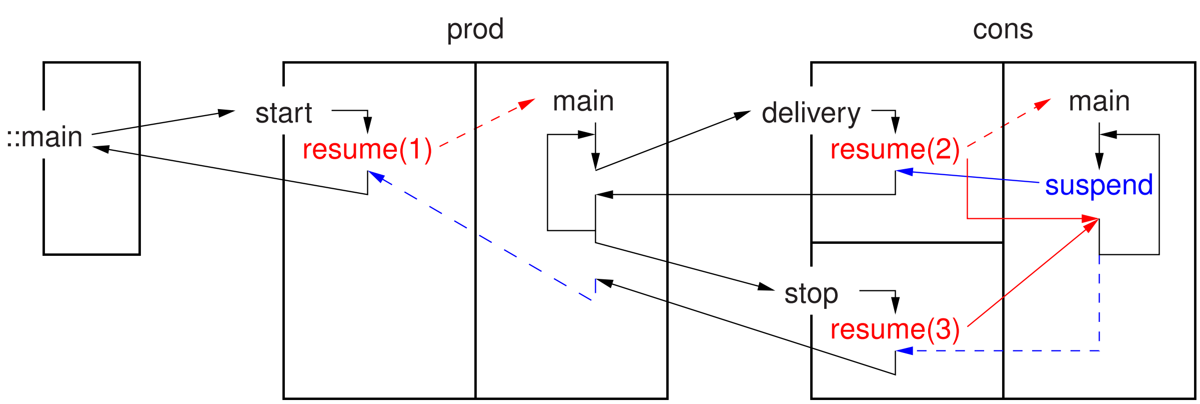
3.9.3 Producer-Consumer

```
_Coroutine Cons {
    int p1, p2, status;  bool done;
    void main() { // starter prod
        // 1st resume starts here
        int money = 1;
        for ( ; ! done; ) {
            cout << "cons " << p1 << " "
                << p2 << " pay $"
                << money << endl;
            status += 1;
            suspend();               // activate delivery or stop
            money += 1;
        }
        cout << "cons stops" << endl;
    } // suspend / resume(starter)
  public:
    Cons() : status(0), done(false) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume();                    // activate main
        return status;
    }
    void stop() { done = true;  resume(); } // activate main
};

_Coroutine Prod {
    Cons & c;
    int N;
    void main() { // starter ::main
        // 1st resume starts here
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100; // products
            int p2 = rand() % 100;
            cout << "prod " << p1
                << " " << p2 << endl;
            int status = c.delivery( p1, p2 );
            cout << " stat " << status << endl;
        }
        c.stop();
        cout << "prod stops" << endl;
    } // suspend / resume(starter)

  public:
    Prod( Cons & c ) : c(c) {}
    void start( int N ) {
        Prod::N = N;
        resume();                // activate main
    }
};
```

```
int main() {
    Cons cons;                    // create consumer
    Prod prod( cons );            // create producer
    prod.start( 5 );              // start producer
}
```



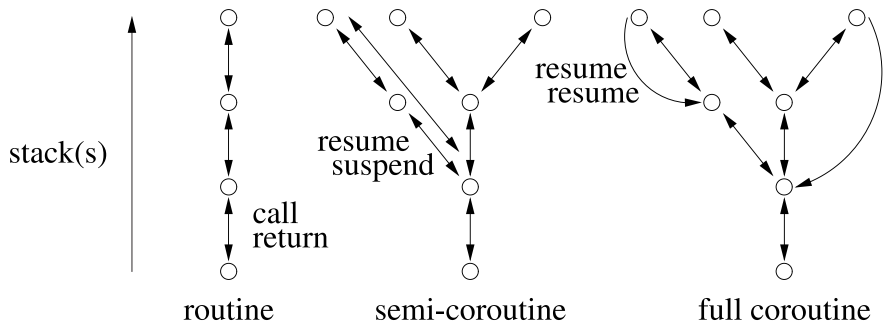
- Do both Prod and Cons need to be coroutines?
- When coroutine main returns, it activates the coroutine that *started* main.
- The **starter** coroutine is the coroutine that does the first resume (cocall).
  - prod started cons.main, so control goes to prod suspended in stop.
  - ::main started prod.main, so control goes to ::main suspended in start.
- For semi-coroutines, the starter is often the last (only) resumer, so it seems coroutine main implicitly suspends on termination.



- **dashed red** ⇒ create stack and resume coroutine main
- **solid red** ⇒ resume coroutine at last suspend
- **solid blue** ⇒ resume last resumer
- **dashed blue** ⇒ resume *starter*

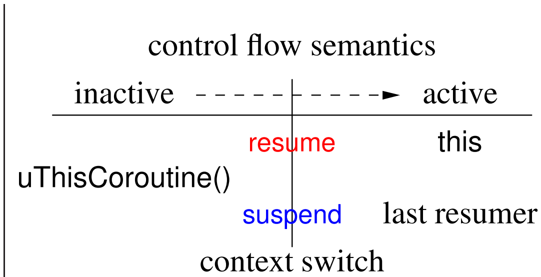
3.10 Full Coroutines

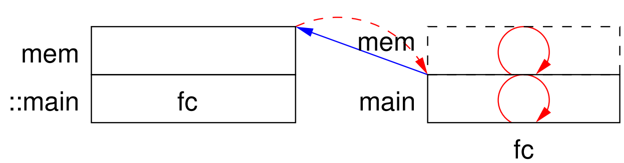
- **Semi-coroutine** activates the member routine that activated it.
- **Full coroutine** has a resume cycle; semi-coroutine does not form a resume cycle.

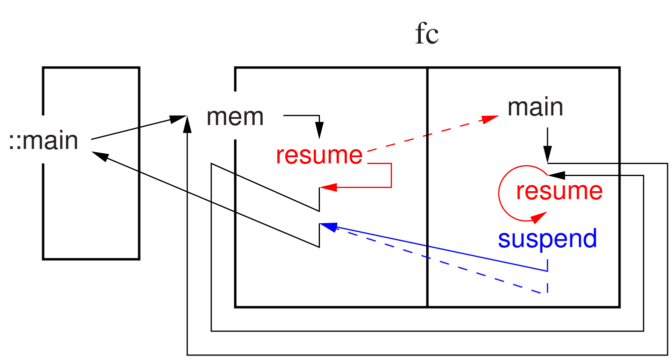


- A full coroutine is allowed to perform semi-coroutine operations because it subsumes the notion of semi-coroutine.

```
_Coroutine Fc {
      void main() { // starter ::main
            mem();         // ?
            resume();      // ?
            suspend();     // ?
      }                    // ?
   public:
      void mem() { resume(); }
};
int main() {
      Fc fc;
      fc.mem();
}
```







- Suspend inactivates the current active coroutine (uThisCoroutine), and activates last resumer.
- Resume inactivates the current active coroutine (uThisCoroutine), and activates the current object (**this**).
- Hence, the current object *must* be a non-terminated coroutine.
- Note, **this** and uThisCoroutine change at different times.
- Exception: last resumer not changed when resuming self because no practical value.
- Full coroutines can form an arbitrary topology with an arbitrary number of coroutines.
- There are 3 phases to any full coroutine program.
  1. starting the cycle
  2. executing the cycle
  3. stopping the cycle (return to the program main)
- Starting the cycle requires each coroutine to know at least one other coroutine.
- The problem is mutually recursive references.

```
Fc x(y), y(x);   // does not compile, why?
```

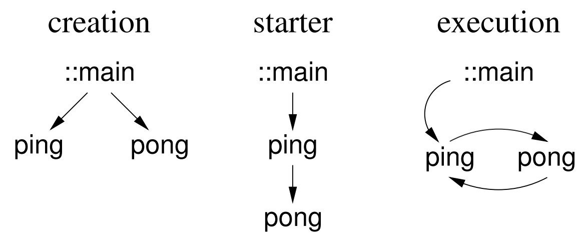
- One solution is to make closing the cycle a special case.

```
Fc x, y(x);
x.partner( y );
```

- Once the cycle is created, execution around the cycle can begin.
- Stopping can be as complex as starting, ***because a coroutine goes back to its starter***.
- For full-coroutines, the starter is often *not* the last resumer, so coroutine main does not appear to implicitly suspend on termination.
- But it is necessary to activate the program main to finish (unless exit is used).
- The starter stack always gets back to the program main.
- Again, it is unnecessary to terminate all coroutines, just delete them.

3.10.1 Ping/Pong

- Full-coroutine control-flow with 2 identical coroutines:

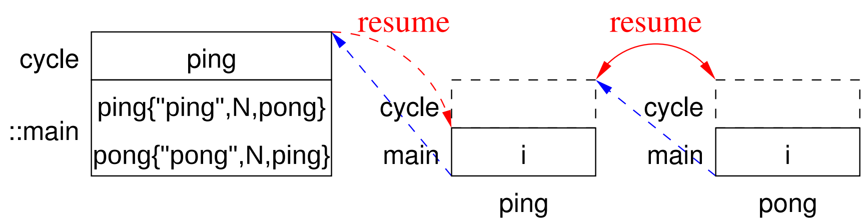


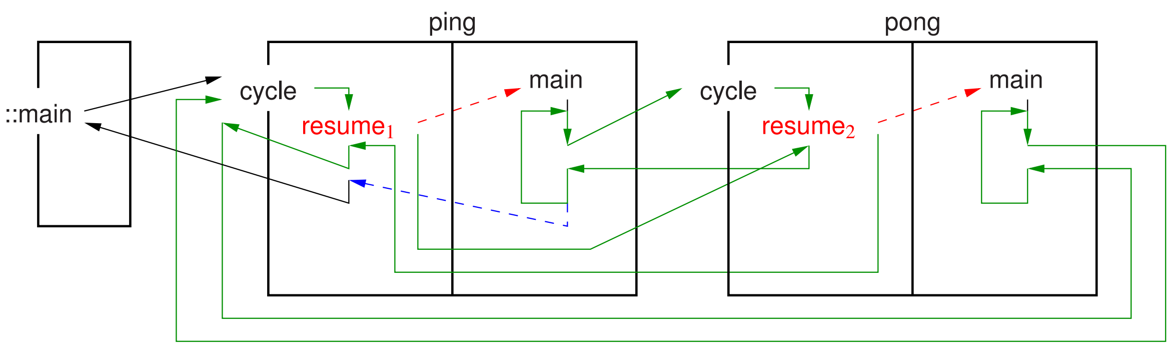

```
_Coroutine PingPong {
    const char * name;
    const unsigned int N;
    PingPong * part;
    void main() {  // ping's starter ::main, pong's starter ping
        for ( unsigned int i = 0; i < N; i += 1 ) {
            cout << name << endl;
            part->cycle();
        }
    }
  public:
    PingPong( const char * name, unsigned int N, PingPong & part )
        : name( name ), N( N ), part( &part ) {}
    PingPong( const char * name, unsigned int N ) : name( name ), N( N ) {}
    void partner( PingPong & part ) { PingPong::part = &part; }
    void cycle() { resume(); }
};
int main() {
    enum { N = 20 };
    PingPong ping( "ping", N + 1 ), pong( "pong", N, ping );
    ping.partner( pong );
    ping.cycle();
}
```

- ping created without partner; pong created with partner.
- ping makes pong partner, closing cycle.
- Why is PingPong::part a pointer rather than reference?
- cycle resumes ping ⇒ ::main is ping's starter
- ping calls pong's cycle member, resuming pong so ping is pong's starter.
- pong calls ping's cycle member, **resuming ping in pong's cycle member**.
- Each coroutine cycles N times, **becoming inactive in the other's cycle member**.
  - ping ends first, because it started first, resuming its starter ::main in ping's cycle member.

- ::main terminates with terminated coroutine ping and unterminated coroutine pong.

- Assume ping's declaration is changed to ping("ping", N + 1).
  - pong ends first, resuming its starter ping in pong's cycle member.
  - ping ends second, resuming its starter ::main in ping's cycle member.
  - ::main terminates with terminated coroutines ping and pong.





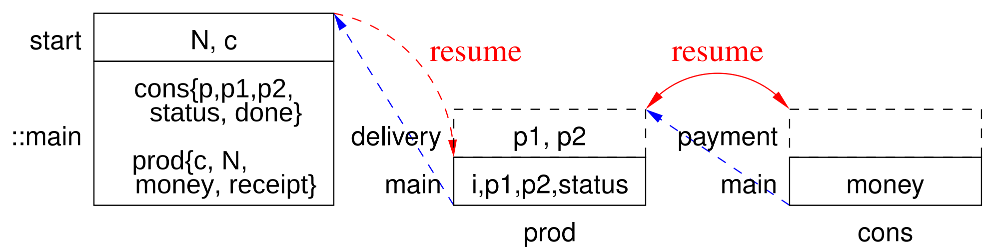
3.10.2 Producer-Consumer

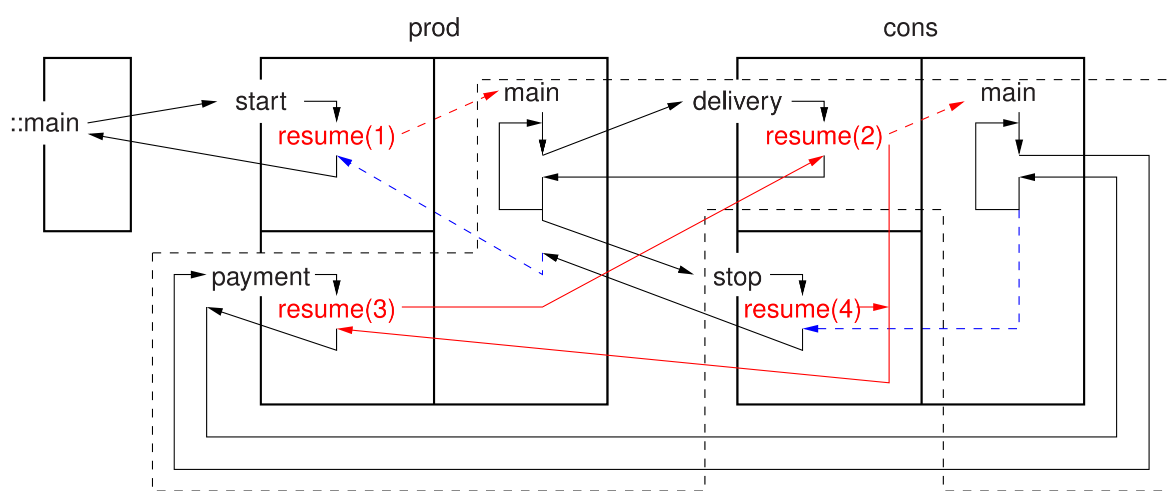
- Full-coroutine control-flow and bidirectional communication with 2 non-identical coroutines:

```
_Coroutine Prod {
    Cons * c;
    int N, money, receipt;
    void main() { // starter ::main
        // 1st resume starts here
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100; // products
            int p2 = rand() % 100;
            cout << "prod " << p1
                << " " << p2 << endl;
            int status = c->delivery(p1, p2);
            cout << "prod rec $" << money
              << " stat " << status << endl;
            receipt += 1;
        }
        c->stop();
        cout << "prod stops" << endl;
    }
  public:
    int payment( int money ) {
        Prod::money = money;
        resume();       // activate prod in
        return receipt; // Cons::delivery
    }
    void start( int N, Cons & c ) {
        Prod::N = N; Prod::c = &c;
        receipt = 0;
        resume(); // activate Prod::main
    }
};
```

```
_Coroutine Cons {
    Prod & p;
    int p1, p2, status;
    bool done;
    void main() { // starter prod
        // 1st resume starts here
        int money = 1, receipt;
        for ( ; ! done; ) {
            cout << "cons " << p1 << " "
                 << p2 << " pay $"
                 << money << endl;
            status += 1;
            receipt = p.payment(money);
            cout << "cons #"
                 << receipt << endl;
            money += 1;
        }
        cout << "cons stops" << endl;
    }
  public:
    Cons(Prod & p) : p(p), status(0), done(false) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume(); // Cons::main 1st time, then
        return status; // cons in Prod::payment
    }
    void stop() {
        done = true;
        resume(); // cons in Prod::payment
    }
};
int main() {
    Prod prod;
    Cons cons( prod );
    prod.start( 5, cons );
}
```

- Cheat using forward reference for Cons at c−>delivery and c−>stop. Fix by?





- Black dashed-line same control flow as ping/pong.
- Remove flag variable from full-coroutine producer-consumer.

```
_Exception Stop {};
_Coroutine Prod {
    Cons * c;
    int N, money, receipt;
    void main() {
        for ( int i = 0; i < N; i += 1 ) {
            int p1 = rand() % 100;
            int p2 = rand() % 100;
            cout << "prod " << ...
            int status = c->delivery(p1, p2);
            cout << "prod rec $" << ...
            receipt += 1;
        }
        _Resume Stop() _At *c;
        suspend(); // restart cons
        cout << "prod stops" << endl;
    }
  public:
    int payment( int money ) {
        Prod::money = money;
        resume();
        return receipt;
    }
    void start( int N, Cons & c ) {
        Prod::N = N; Prod::c = &c;
        receipt = 0;
        resume();
    }
};
```

```
_Coroutine Cons {
    Prod & p;
    int p1, p2, status = 0;
    void main() {
        int money = 1, receipt;
        try {
            for ( ;; ) {
                cout << "cons " << p1 << ...
                status += 1;
                receipt = p.payment( money );
                cout << "cons #" << ...
                money += 1;
                _Enable; // trigger exception
            }
        } catch( Stop & ) {}
        cout << "cons stops" << endl;
    }
  public:
    Cons( Prod & p ) : p( p ) {}
    int delivery( int p1, int p2 ) {
        Cons::p1 = p1; Cons::p2 = p2;
        resume();
        return status;
    }
};
```

3.11 Coroutine Languages

- Coroutine implementations have two forms:

    1. stackless: use the caller's stack and a fixed-sized local-state
    2. stackful: separate stack and a fixed-sized (class) local-state

- Stackless coroutines cannot call other routines and then suspend, i.e., only suspend in the coroutine main.
- Generators/iterators are often simple enough to be stackless using yield.
- Simula, CLU, C#, Ruby, Python, JavaScript, Lua, F# all support yield constructs.

3.11.1 Python 3.5

- Stackless, semi coroutines, routine versus class, no calls, single interface
- Fibonacci (see Section 3.1.1.4, p. 28)

```
def Fibonacci( n ):                     # coroutine main
    fn = 0;  fn1 = fn
    yield fn                            # suspend
    fn = 1; fn2 = fn1; fn1 = fn
    yield fn                            # suspend
    # while True:                       # for infinite generator
    for i in range( n - 2 ):
        fn = fn1 + fn2; fn2 = fn1; fn1 = fn
        yield fn                        # suspend

f1 = Fibonacci( 10 )                    # objects
f2 = Fibonacci( 10 )
for i in range( 10 ):
    print( next( f1 ), next( f2 ) )     # resume
for fib in Fibonacci( 15 ):             # use generator as iterator
    print( fib )
```

- Format (see Section 3.1.2.4, p. 32)

```
def Format():
    try:
        while True:
            for g in range( 5 ):        # groups of 5 blocks
                for b in range( 4 ):    # blocks of 4 characters
                    print( (yield), end='' ) # receive from send
                print( '  ', end='' ) # block separator
            print()                     # group separator
    except GeneratorExit:               # destructor
        if g != 0 | b != 0:             # special case
            print()

fmt = Format()
next( fmt )                             # prime generator
for i in range( 41 ):
    fmt.send( 'a' )                     # send to yield
```

- send takes only one argument, and no cycles ⇒ no full coroutine

3.11.2 JavaScript

- Similar to Python: stackless, semi coroutines, routine versus class, no calls, single interface
- Embedded in HTML with I/O from web browser.
- Fibonacci (see Section 3.1.1.4, p. 28)

```
<!DOCTYPE html><html>
<head><meta charset="utf-8" /><title>Fibonacci Coroutine</title></head>
<body><button id="button">Click for next Fibonacci number!</button>
    <p id="output"></p></body>
<script>
```

```
function * Fibonacci() {
    var fn = 0, fn1 = 0, fn2 = 0;       // JS bug: initialize vars or lost on suspend
    yield fn;                           // return fn to resumer
    fn = 1; fn2 = fn1; fn1 = fn;
    yield fn;                           // return fn to resumer
    for ( ;; ) {
        fn = fn1 + fn2; fn2 = fn1; fn1 = fn;
        yield fn;                       // return fn to resumer
    }
}
const button = document.getElementById( 'button' );
const output = document.getElementById( 'output' );
var count = 0, suffix;
var fib = Fibonacci();
button.addEventListener( "click", event => {
    if (count % 10 == 1) suffix = "st";
    else if (count % 10 == 2) suffix = "nd";
    else suffix = "th";
    output.textContent = count + suffix + " Fibonacci: " + fib.next().value;
    count += 1;
});
</script></body></html>
```

- Format (see Section 3.1.2.4, p. 32)

```
<!DOCTYPE html><html>
<head><meta charset="utf-8" /><title>Format Coroutine</title></head>
<body><input placeholder="Type characters!" size=50><p id="output"></p></body>
<script>
function * Format() {
    var g = 0, b = 0, ch = '';     // JS bug: initialize vars or lost on suspend
    for ( ;; ) {
        for ( g = 0; g < 5; g += 1 ) {
            for (b = 0; b < 4; b += 1) {
                ch = yield;
                output.innerHTML += ch; // console.log adds \n
            }
            output.innerHTML  += "  ";
        }
        output.innerHTML += "<br>";
    }
}
const inputBox = document.querySelector( 'input' );
const output = document.getElementById( 'output' );
var format = Format();
format.next();                     // prime generator
inputBox.addEventListener( 'keypress', event => {
    format.next( event.key );
});
</script></body></html>
```

- FSM – detects 3 consecutive matching characters

```
<!DOCTYPE html><html>
<head><meta charset="utf-8" /><title>Consecutive characters</title></head>
<body><input placeholder="Type characters!" size=50><p id="output"></p></body>
<script>

function * HandleKeyEvent() {
    var ch = '', prevCh = '';          // JS bug: initialize vars or lost on suspend
    for ( ;; ) {
        prevCh = ch;
        for ( var i = 1;; i += 1 ) {
            ch = yield;
            if ( ch != prevCh ) break;
            if ( i == 2 ) {
                output.textContent = "3 consecutive characters!";
                ch = yield;
                output.textContent = "";
                i = 0;
            }
        }
    }
}

const inputBox = document.querySelector( 'input' );
const output = document.getElementById( 'output' );
var handler = HandleKeyEvent();
handler.next();                        // prime generator
inputBox.addEventListener( 'keypress', event => {
    handler.next( event.key );
});
</script></body></html>
```

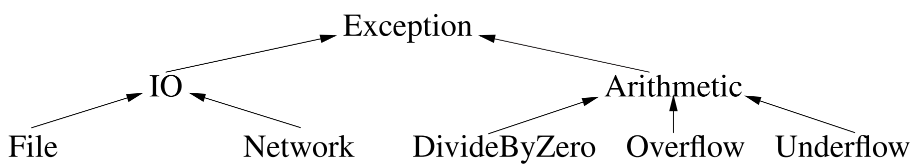
3.11.3 C++20 Coroutines

- C++20 has an API for coroutines and outline code to build stackless, stackful, or even fibres (tasks without preemption).
- This capability cannot be used directly. It requires writing significant low-level implementation code.

4 More Exceptions

4.1 Derived Exception-Type

- **derived exception-types** is a mechanism for inheritance of exception types, like inheritance of classes.
- Provides a kind of polymorphism among exception types:



- Provides ability to handle an exception at different degrees of specificity along the hierarchy.
- Possible to catch a more general exception-type in higher-level code where the implementation details are unknown.
- Higher-level code should catch general exception-types to reduce tight coupling to the specific implementation.
  - tight coupling may force unnecessary changes in the higher-level code when low-level code changes.
- Exception-type inheritance allows a handler to match multiple exceptions, e.g., a base handler can catch both base and derived exception-type.
- To handle this case, most propagation mechanisms perform a linear search of the handlers for a guarded block and select the first matching handler.

```
try { . . .
} catch( Arithmetic & ) { . . .
} catch( Overflow ) { . . . // never selected!!!
}
```

- When subclassing, it is best to catch an exception by reference:

```
struct B {};
struct D : public B {};
try {
    throw D(); // _Throw in uC++
} catch( B e ) { // truncation
    // cannot down-cast
}
```

```
try {
    throw D(); // _Throw in uC++
} catch( B & e ) { // no truncation
    . . . dynamic_cast<D>(e) . . .
}
```

  - Otherwise, exception is truncated from its dynamic type to static type specified at the handler, and cannot be down-cast to the dynamic type.
- Notice, catching truncation (see page 59) is different from raising truncation, which does not occur in μC++ with **_Throw**.

4.2 Catch-Any

- **catch-any** is a mechanism to match any exception propagating through a guarded block.
- With exception-type inheritance, catch-any can be provided by the root exception-type, e.g., **catch**(Exception) in Java.
- Otherwise, special syntax is needed, e.g., **catch**(...) in C++.
- For termination, catch-any is used as a general cleanup when a non-specific exception occurs.
- For resumption, this capability allows a guarded block to gather or generate information about control flow (e.g., logging).

```
try {
    ...
} _CatchResume( ... ) { // catch-any
    ...             // logging
    _Resume;        // reresume for fixup
} catch( ... ) {    // catch-any
    ...             // cleanup
    _Throw;         // rethrow for recovery
}
```

- Java finalization:

```
try { ...
} catch( E ) { ... }
... // other catch clauses
} finally { // always executed
    ... // cleanup
    // possibly rethrow
}
```

  provides catch-any capabilities and handles the non-exceptional case.

  - difficult to mimic in C++, even with RAII, because of local variables.

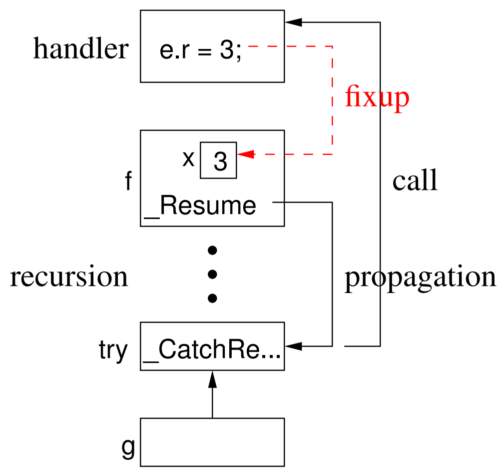
4.3 Exception Parameters

- **Exception parameters** allow passing information from the raise to a handler.
- Inform a handler about details of the exception, and to modify the raise site to fix an exceptional situation.
- Different EHMs provide different ways to pass parameters.
- In C++/Java, parameters are defined inside the exception:

```
struct E {
    int i;
    E( int i ) : i(i) {}
};
void f( ... ) { ... throw E( 3 ); ... } // argument
int main() {
    try {
        f( ... );
    } catch( E p ) { // parameter, value or reference
        ... p.i ...
    }
}
```

- For resumption, values at raise modified via reference/pointer in caught exception:

```
_Exception E {
  public:
    int & r;
    E( int & r ) : r( r ) {}
};
void f() {
    int x;
    ... _Resume E( x ); ...
}
void g() {
    try {
        f();
    } _CatchResume( E & e ) {
        ... e.r = 3; ...
    }
}
```



4.4 Exception List

- Missing exception handler for arithmetic overflow in control software caused Ariane 5 rocket to self-destruct ($370 million loss).
- **exception list** is part of a routine's prototype specifying which exception types may propagate from the routine to its caller.

```
int g() throw(E) { ... throw E(); }
```

- This capability allows:
  - static detection of a raised exception not handled locally or by its caller
  - runtime detection where the exception may be converted into a special **failure exception** or the program terminated.
- 2 kinds of checking:

  - checked/unchecked exception-type (Java, inheritance based, static check)
  - checked/unchecked routines (C++, exception-list based, dynamic check) (deprecated C++11, replaced with **noexcept**)

- While checked exception-types are useful for software engineering, reuse is precluded.

- E.g., consider the simplified C++ template routine sort:

```
template<class T> void sort( T items[ ] ) throw( ?, ?, ... ) {
    // using bool operator<( const T &a, const T &b );
```

  using the operator routine < in its definition.

- Impossible to know all exception types that propagated from routine < for every type.

- Since only a fixed set of exception types can appear in sort's exception list, some sortable types are precluded.

- Exception lists can preclude reuse for arguments of routine pointers (functional style) and/or polymorphic methods/routines (OO style):

```
struct E {};
// throw NO exceptions
void f( void (*p)() noexcept ) {
    p();
}
void g() noexcept(false) { throw E(); }
void h() {
    try { . . . f( g ); . . .
    } catch( E ) {}
}
```

```
struct B { // throw NO exceptions
    virtual void g() noexcept {}
    void f() { g(); }
};
struct D : public B {
    void g() noexcept(false) { throw E(); }
    void h() {
        try { . . . f(); . . .
        } catch( E ) {}
    }
};
```

- Left example, routine h has an appropriate **try** block and passes the version of g to f that raises exception-type E.

- However, checked exception-types preclude this case because the signature of argument g is less restrictive than parameter p of f.

- Right example, member routine D::h calls B::f, which calls D::g that raises exception-type E.

- However, checked exception types preclude this case because the signature of D::g is less restrictive than B::g.

- Finally, determining an exception list for a routine can become impossible for concurrent exceptions because they can propagate at any time.

4.5 Destructor

- Destructor is implicitly **noexcept** ⇒ ***cannot*** raise an exception.
- Destructor ***can*** raise an exception, if marked **noexcept**(**false**), or inherits from class with **noexcept**(**false**) destructor.

```
struct E {};
struct C {
    ~C() noexcept(false) { throw E(); }     y's destructor         x's destructor
};                                               | throw E              | throw E
try {           // outer try                inner try              outer try
    C x;        // raise on deallocation         | y                    | x
    try {       // inner try
        C y; // raise on deallocation
    } catch( E ) {...}  // inner handler
} catch( E ) {...}  // outer handler
```

- ○ y's destructor called at end of inner **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at inner **catch**
- ○ x's destructor called at end of outer **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at outer **catch**

4.6 Multiple Exceptions

- An exception handler can generated an arbitrary number of nested exceptions.

```
struct E {};                           h  f̸
int cnt = 3;                              f
void f( int i ) {                         f
    if ( i == 0 ) throw E();           h  f̸  throw E2
    try {                                 f
        f( i - 1 );                       f
    } catch( E ) { // handler h        h  f̸  throw E1
        cnt -= 1;                         f
        if ( cnt > 0 ) f( 2 );            f
        ... throw; ...
    }
}
int main() { f( 2 ); }
```

- Exceptions are nested as handler can rethrow its matched exception when control returned.
- However, multiple exceptions cannot propagate simultaneously.
- Only destructor code can intervene during propagation.
- Hence, a destructor ***cannot*** raise an exception during propagation; it can only start propagation.

```
try {
    C x;            // raise on deallocation
    throw E();
} catch( E ) {...}
```

- Raise of E causes unwind of inner **try** block.
- x's destructor called during unwind, it raises an exception E, which one should be used?
  - Cannot start second exception without handler to deal with first exception, i.e., cannot drop exception and start another.
  - Cannot postpone first exception because second exception may remove its handlers during stack unwinding.
- Check if exception is being propagated with uncaught_exceptions().

5 Concurrency

- A **thread** is an independent sequential execution path through a program.
  - Each thread is scheduled for execution separately and independently from other threads.
- A **process** is a program component (like a routine) that **has its own thread** and has the same state information as a coroutine.
- A **task** is similar to a process except that it is
  - reduced along some particular dimension (like the difference between a boat and a ship, one is physically smaller than the other).
  - It is often the case that a process has its own memory, while tasks share a common memory.
  - A task is sometimes called a light-weight process (LWP).
- **Parallel execution** is when 2 or more operations occur simultaneously, which can only occur when multiple processors (CPUs) are present.
- **Concurrent execution** is any situation in which execution of multiple threads *appears* to be performed in parallel.
  - It is the threads of control associated with processes and tasks that results in concurrent execution, **not the processors**.

5.1 Why Write Concurrent Programs

- Dividing a problem into multiple executing threads is an important programming technique just like dividing a problem into multiple routines.
- Expressing a problem with multiple executing threads may be the natural (best) way of describing it.
- Multiple executing threads can enhance execution-time efficiency by taking advantage of inherent concurrency in an algorithm and any parallelism available in the computer system.

5.2 Why Concurrency is Difficult

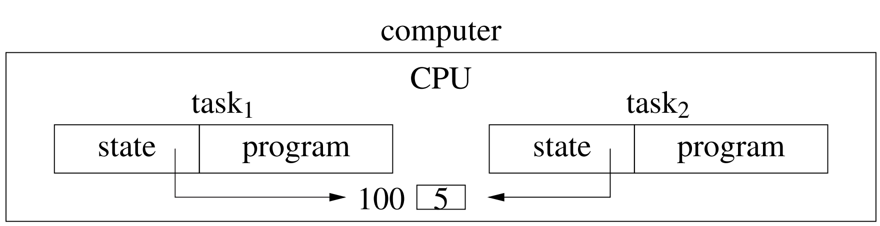
- to understand:
  - While people can do several things concurrently, the number is small because of the difficulty in managing and coordinating them.
  - Especially when the things interact with one another.
- to specify:
  - How can/should a problem be broken up so that parts of it can be solved at the same time as other parts?

- ◦ How and when do these parts interact or are they independent?
- ◦ If interaction is necessary, what information must be communicated during the interaction?

- to debug:
  - ◦ Concurrent operations proceed at varying speeds and in non-deterministic order, hence execution is not repeatable (Heisenbug).
  - ◦ Reasoning about multiple streams or threads of execution and their interactions is much more complex than for a single thread.
- E.g. Moving furniture out of a room; can't do it alone, but how many helpers and how to do it quickly to minimize the cost?
- How many helpers?
  - ◦ 1,2,3, ... N, where N is the number of items of furniture
  - ◦ more than N?
- Where are the bottlenecks?
  - ◦ the door out of the room, items in front of other items, large items
- What communication is necessary between the helpers?
  - ◦ which item to take next
  - ◦ some are fragile and need special care
  - ◦ big items need several helpers working together

5.3 Concurrent Hardware

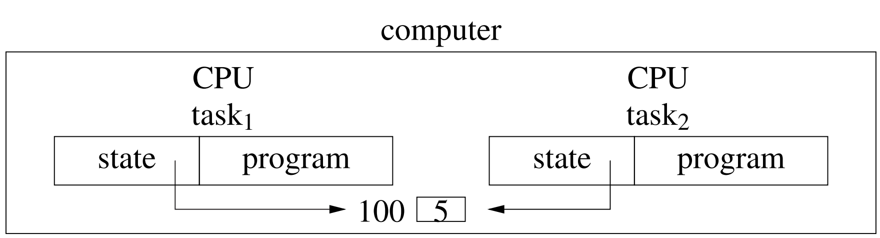
- Concurrent execution of threads is possible with only one CPU (**uniprocessor**); **multitasking** for multiple tasks or **multiprocessing** for multiple processes.



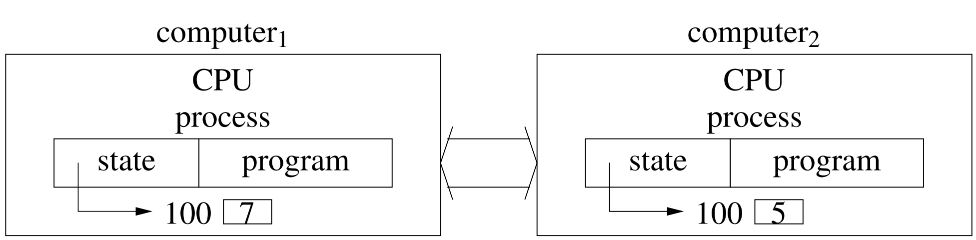
  - ◦ Parallelism is simulated by context switching the threads on the CPU.
  - ◦ Most of the issues in concurrency can be illustrated without parallelism.
  - ◦ Pointers among tasks work because memory is shared.
  - ◦ **Unlike coroutines, task switching may occur at non-deterministic program locations, i.e., between any two *machine* instructions.**

- Introduces all the difficulties in concurrent programs.
  - programs must be written to work regardless of non-deterministic ordering of program execution.
- Switching happens *explicitly* but conditionally when calling routines.
  - routine may or may not context switch depending on hidden (internal) state (cannot predict)
- Switching can happen *implicitly* because of an external **interrupt** independent of program execution.
  - e.g., I/O or timer interrupt;
  - timer interrupts divide execution (between instructions) into discrete time-slices occurring at non-deterministic time intervals
  - **⇒ task execution is not continuous**
- If interrupts affect **scheduling** (execution order), it is called **preemptive**, otherwise the scheduling is **non-preemptive**.
- Programmer cannot predict execution order, unlike coroutines.
- Granularity of context-switch is instruction level for preemptive (harder to reason) and routine level for non-preemptive.

- In fact, every computer has multiple CPUs: main CPU(s), bus CPU, graphics CPU, disk CPU, network CPU, etc.
- Concurrent/parallel execution of threads is possible with multiple CPUs sharing memory (**multiprocessor**):



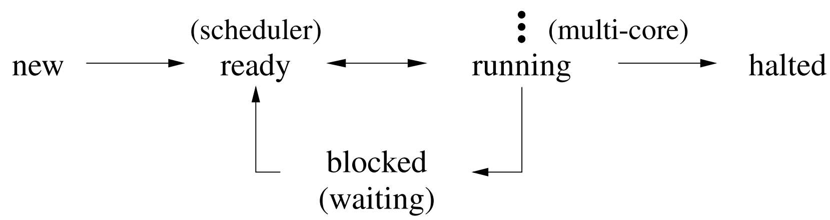
- Pointers among tasks work because memory is shared.
- Concurrent/parallel execution of threads is possible with single/multiple CPUs on different computers with *separate memories* (**distributed system**):



- Pointers among tasks do NOT work because memory is not shared.

5.4 Execution States

- A thread may go through the following states during its execution.



- **State transition**s are initiated in response to events (e.g., interrupts):
  - entering the system (new → ready)
  - assigning thread to computing resource, e.g., CPU (ready → running)
  - timer alarm for preemption (running → ready)
  - long-term delay versus spinning (running → blocked)
  - completion of delay, e.g., network or I/O completion (blocked → ready)
  - normal completion or error, e.g., segment fault (running → halted)
- Thread cannot bypass the "ready" state during a transition so the scheduler maintains complete control of the system.
- Non-deterministic "ready ↔ running" transition ⇒ basic operations unsafe:

```
int i = 0;      // shared
task0           task1
i += 1          i += 1
```

- If increment implemented with single **inc i** instruction, transitions can only occur before or after instruction, not during.
- If increment is replaced by a load-store sequence, transitions can occur during sequence.

```
ld   r1,i       // load into register 1 the value of i
...             // PREEMPTION
add r1,#1       // add 1 to register 1
...             // PREEMPTION
st   r1,i       // store register 1 into i
```

- If both tasks increment 10 times, the expected result is 20.
- True for single instruction, false for load-store sequence.
- Many failure cases for load-store sequence where i does not reach 20.

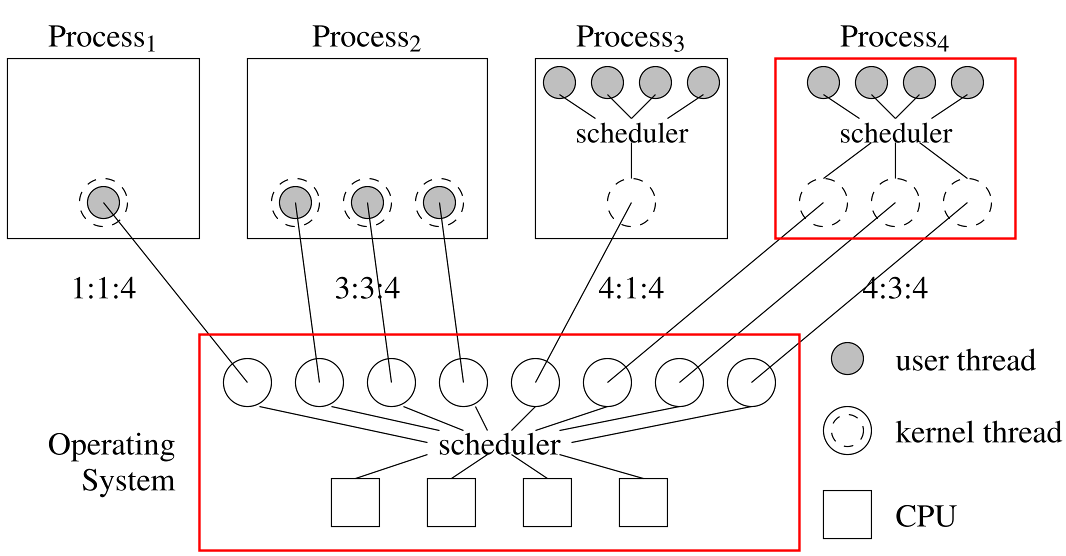
- Remember, context switch saves and restores registers for each coroutine/task.

```
            task0                        task1
1st iteration
ld   r1,i        (r1 <- 0)
add  r1,#1       (r1 <- 1)
                                 1st iteration
                                 ld   r1,i        (r1 <- 0)
                                 add  r1,#1       (r1 <- 1)
                                 st   r1,i        (i  <- 1)
                                 2nd iteration
                                 ld   r1,i        (r1 <- 1)
                                 add  r1,#1       (r1 <- 2)
                                 st   r1,i        (i  <- 2)
                                 3rd iteration
                                 ld   r1,i        (r1 <- 2)
                                 add  r1,#1       (r1 <- 3)
                                 st   r1,i        (i  <- 3)
1st iteration
st   r1,i        (i  <- 1)
```

- The 3 iterations of **task1** are lost when overwritten by **task0**.
- Hence, sequential operations, however small (increment), are unsafe in a concurrent program.

5.5 Threading Model

- For multiprocessor systems, a **threading model** defines relationship between threads and CPUs.
- OS manages CPUs providing logical access via **kernel threads** (**virtual processors**) *scheduled* across the CPUs.



- More kernel threads than CPUs to provide multiprocessing, i.e., run multiple programs simultaneously.
- A process may have multiple kernel threads to provide parallelism if multiple CPUs.
- A program may have user threads scheduled on its process's kernel threads.
- User threads are a low-cost structuring mechanism, like routines, objects, coroutines (versus high-cost kernel thread).
- Relationship is denoted by user:kernel:CPU, where:
  - 1:1:C (kernel threading) – 1 user thread maps to 1 kernel thread
  - N:N:C (generalize kernel threading) – N $\times$ 1:1 kernel threads (Java/Pthreads/C++)
  - M:1:C (user threading) – M user threads map to 1 kernel thread (no parallelism)
  - M:N:C (user threading) – M user threads map to N kernel threads (Go, μC++)
- Often the CPU number (C) is omitted.
- Can recursively add **nano threads** (stackless) on top of user threads (stackful), and **virtual machine** below OS.

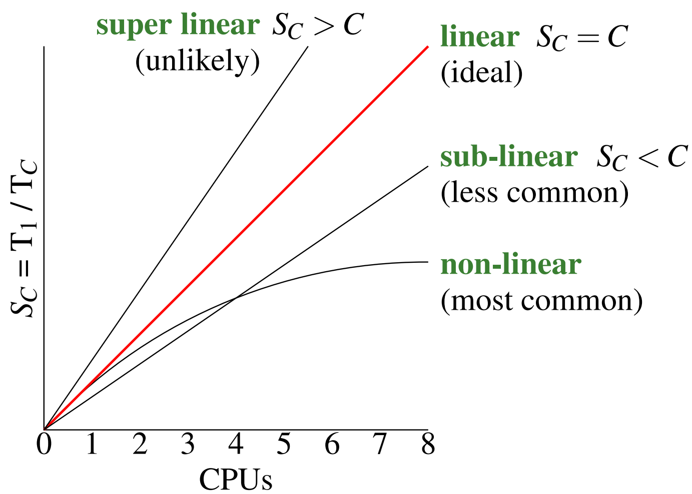
5.6 Concurrent Systems

- Concurrent systems can be divided into 3 major types:
  1. those that attempt to **discover** ***implicit*** concurrency in an otherwise sequential program, e.g., parallelizing loops and access to data structures
  2. those that provide concurrency through ***implicit*** constructs, which a programmer uses to build a concurrent program
  3. those that provide concurrency through ***explicit*** constructs, which a programmer uses to build a concurrent program
- In type 1, there is a fundamental limit to how much concurrency can be found and current techniques only work on a certain class of problems.
- In type 2, concurrency is accessed indirectly via specialized mechanisms (e.g., pragmas or parallel **for**) and threads are implicitly managed.
- In type 3, concurrency is accessed directly and threads explicitly managed.
- Types 1 & 2 are always built from type 3.
- **To solve all concurrency problems, threads need to be explicit.**
- Both implicit and explicit mechanisms are complementary, and hence, can appear together in a single programming language.

- However, the limitations of implicit mechanisms require that explicit mechanisms always be available to achieve maximum concurrency.
- Some concurrent systems provide a single technique or paradigm that must be used to solve all concurrent problems.
- While a particular paradigm may be very good for solving certain kinds of problems, it may be awkward or preclude other kinds of solutions.
- Therefore, a good concurrent system must support a variety of different concurrent approaches, while at the same time not requiring the programmer to work at too low a level.
- In all cases, as concurrency increases, so does the complexity to express and manage it.

5.7 Speedup

- Program **speedup** is $S_C = T_1/T_C$, where C is number of CPUs and T_1 is sequential execution.
- E.g., 1 CPU takes 10 seconds, $T_1 = 10$ (**user time**), 4 CPUs takes 2.5 seconds, $T_4 = 2.5$ (**real time**) $\Rightarrow S_4 = 10/2.5 = 4$ times speedup (linear).



- Aspects affecting speedup (assume sufficient parallelism for concurrency):
  1. amount of concurrency
  2. critical path among concurrency
  3. scheduler efficiency
- An algorithm/program is composed of sequential and concurrent sections.
- E.g., sequentially read matrix, concurrently subtotal rows, sequentially total subtotals.
- **Amdahl's law** (Gene Amdahl): concurrent section of program is P making sequential section $1-P$, then maximum speedup using C CPUs is:

$$S_C = \frac{1}{(1-P)+P/C} \quad where\ T_1 = 1, T_C = sequential + concurrent$$

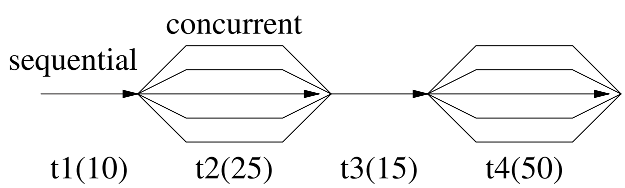
- Normalize: $T_1 = 10/10 = 1$, $T_4 = 2.5/10 = .25$.

$$S_4 = \frac{1}{(1-1)+1\times.25} = 4\ \ times,\ P = 1 \Rightarrow (100\%)\ of\ T_4\ is\ concurrent$$

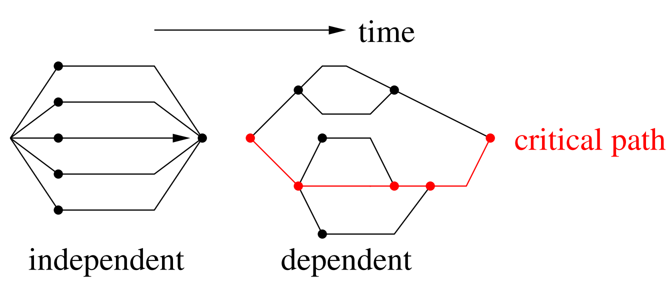
- Change $P = .8(80\%)$ so $T_4 = .8\times.25 = .2$ is concurrent and $1-.8 = .2(20\%)$ is sequential.

$$S_4 = \frac{1}{(1-.8)+.8\times.25} = \frac{1}{.2+.2} = 2.5\ \ times,\ because\ of\ sequential\ code$$

- As C goes to infinity, P/C goes to 0, so maximum speedup is $1/(1-P)$, i.e., time for sequential section.
- Speedup falls rapidly as sequential section $(1-P)$ increases.
- E.g., sequential section = $.2(20\%)$, $S_C = 1/(1-.8) \Rightarrow$ max speedup 5.
- **Concurrent programming consists of minimizing sequential section $(1-P)$.**
- E.g., program has 4 stages: $t1$ = 10, $t2$ = 25, $t3$ = 15, $t4$ = 50 (time units)



- T_C = 10 + 25 + 15 + 50 = 100 (time units)
- Concurrently speedup sections $t2$ by 5 times and $t4$ by 10 times.
- T_C = 10 + 25 / 5 + 15 + 50 / 10 = 35 (time units)
  Speedup = 100 / 35 = 2.86 times
- Large reductions for $t2$ and $t4$ have only minor effect on speedup.
- Formula does not consider any increasing costs for the concurrency, i.e., administrative costs, so results are optimistic.
- While sequential sections bound speedup, concurrent sections bound speedup by the **critical path** of computation.



- ◦ **independent execution** : all threads created together and do not interact.
- ◦ **dependent execution** : threads created at different times and interact.

- Longest path bounds speedup (even for independent execution).
- Finally, speedup can be affected by scheduler efficiency/ordering (often no control), e.g.:
  - greedy scheduling : run a thread as long as possible before context switching (not very concurrent).
  - LIFO scheduling : give priority to newly waiting tasks (starvation).
- Therefore, it is difficult to achieve significant speedup for many algorithms/programs.
- In general, benefit comes when many programs achieve some speedup so there is an overall improvement on a multiprocessor computer.

5.8 Thread Creation

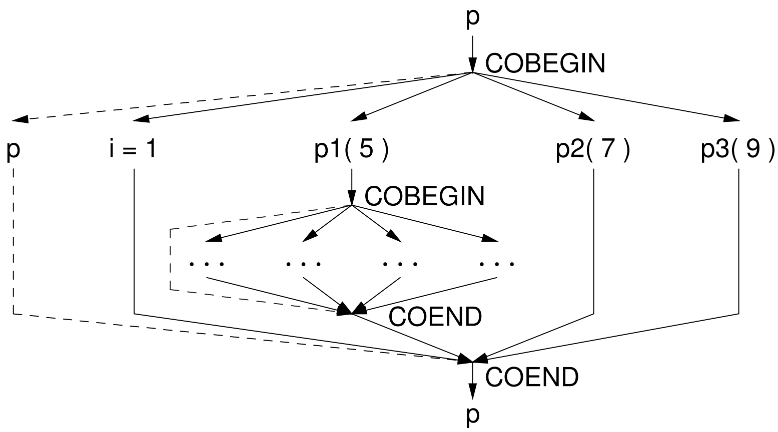
- Concurrency requires 3 mechanisms in a programming language.
  1. creation – cause another thread of control to come into existence.
  2. synchronization – establish timing relationships among threads, e.g., same time, same rate, happens before/after.
  3. communication – transmit data among threads.
- Thread creation must be a primitive operation; cannot be built from other operations in a language.
- ⇒ need new construct to create a thread and define where the thread starts execution.

5.8.1 COBEGIN/COEND

- Compound statement with statements run by multiple threads.

```
#include <uCobegin.h>
int i;
void p1(...);  void p2(...);  void p3(...);
// initial thread creates threads
COBEGIN                 // threads execute statement in block
    BEGIN i = 1;   ... END
    BEGIN p1( 5 ); ... END        // order and speed of internal
    BEGIN p2( 7 ); ... END        // thread execution is unknown
    BEGIN p3( 9 ); ... END
COEND                   // initial thread waits for all internal threads to
                        // finish (synchronize) before control continues
```

- Implicit or explicit concurrency?
- A **thread graph** represents thread creations:



- Restricted to creating trees (lattice) of threads.
- Use recursion to create dynamic number of threads.

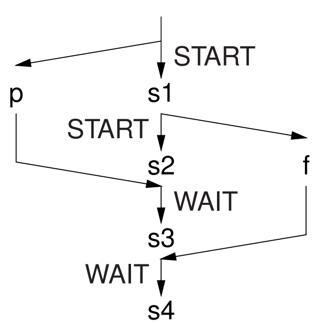
```
void loop( int N ) {
    if ( N != 0 ) {
        COBEGIN
            BEGIN p1( ... ); END
            BEGIN loop( N - 1 ); END // recursive call
        COEND // wait for return of recursive call
    }
}
cin >> N;
loop( N );
```

- What does the thread graph look like?

5.8.2 START/WAIT

- Start thread in routine and wait (join) at thread termination, allowing arbitrary thread graph:

```
#include <uCobegin.h>
int i;
void p( int i ) {...}
int f( int i ) {...}
decltype(START( p, 5 )) tp = START( p, 5 );
s1      // continue execution, do not wait for p
decltype(START( f, 8 )) tf = START( f, 8 );
s2      // continue execution, do not wait for f
WAIT( tp ); // wait for p to finish
s3
i = WAIT( tf ); // wait for f to finish
s4
```



- Allows same routine to be started multiple times with different arguments.
- Implicit or explicit concurrency?

- COBEGIN/COEND can only approximate this thread graph:

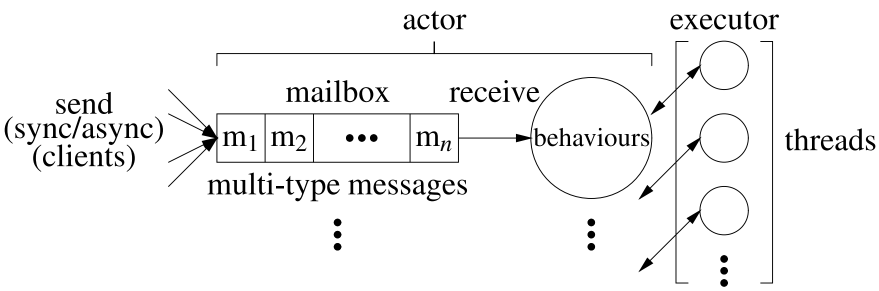
```
COBEGIN
    BEGIN p( 5 ); END
    BEGIN s1;
        COBEGIN
            BEGIN f( 8 ); END
            BEGIN s2; END
        END // wait for f!
    END
COEND
s3; s4;
```

- START/WAIT can simulate COBEGIN/COEND:

```
COBEGIN                        auto t1 = START( p1, ... )
    BEGIN p1(...) END          auto t2 = START( p2, ... )
    BEGIN p2(...) END          WAIT t1
COEND                          WAIT t2
```

5.8.3 Actor

- An **actor** (Hewitt/Agha) is a unit of work *without* a thread, like BEGIN/END.



- An executor thread matches an actor with a message and runs the actor's behaviour, like COBEGIN/COEND
- Communication is via polymorphic queue of messages (mailbox) ⇒ dynamic type-checking.
- Usually no shared information among actors and no blocking is allowed.
- Actor systems in popular languages: CAF (C++), ProtoActor (Go), Akka (Scala).
- Must declare messages and actors.

```
#include <uActor.h>
struct StrMsg : public uActor::Message { // derived message
    string val;                          // string message
    StrMsg( string val ) : Message( uActor::Delete ), // delete after use
                           val( val ) {}
};
```

```
_Actor Hello {  // : public uActor
    Allocation receive( Message & msg ) { // receive base type
        Case( StrMsg, msg ) {        // discriminate derived message
            . . . msg_d->val; . . .  // access derived message
        } else Case( StopMsg, msg ) return Delete; // delete actor
        return Nodelete;             // reuse actor
    }
};
int main() {
    uActor::start();                 // start actor system
    *new Hello() | *new StrMsg( "hello" ) | uActor::stopMsg;
    *new Hello() | *new StrMsg( "bonjour" ) | uActor::stopMsg;
    uActor::stop();                  // wait for all actors to terminate
}
```

- Implicit or explicit concurrency?
- Must start actor system (and create thread pool) (**uActor::start()**).
- Actor must receive at least one message to start.
- Messages received in FIFO order from mailbox and executed sequentially.
- Received *derived* message accessed through name msg_d.
- Send messages with operator |.
- (StartMsg) uActor::startMsg / (StopMsg) uActor::stopMsg persistent predefined messages.
- Must wait for actors to complete (**uActor::stop()**).
- Most actor systems leverage garbage collection to manage actors and messages, and the actor system ends after all actors terminate.
- C++ does not have garbage collection so actors/messages use explicit storage-management returning an allocation status for each actor/message.

```
class uActor {
  public:
    enum Allocation { Nodelete, Delete, Destroy, Finished }; // allocation actions
    struct Message {
        Allocation allocation;               // allocation action
        . . .
    }
    static struct StartMsg : public uActor::SenderMsg {} startMsg; // start actor
    static struct StopMsg : public uActor::SenderMsg {} stopMsg; // terminate actor
    static void start(); // create executor to run actors
    static bool stop(); // wait for all actors to terminate or timeout
 private:
    Allocation allocation;                   // allocation action
};
```

Nodelete ⇒ actor or message persists after an actor returns from receive. Use for multi-use actors or messages during their life time. (message default)

Delete ⇒ actor or message is deleted after an actor returns from receive. Use with dynamically allocated actors or messages at completion.

Destroy ⇒ actor's or message's destructor is called after an actor returns from receive but storage is not deallocated. Use with placement allocated actors or messages at completion.

Finished ⇒ actor is marked finished after it returns from receive but neither the destructor is called nor storage deallocated. (No action for a message.) Use with stack allocated actors or messages at completion.

- The executor finds an actor with messages and passes the first message to the actor to process.
- After the actor returns, the executor checks what to do with the message and actor.

```
#include <uActor.h>
struct StrMsg : public uActor::Message { // default Nodelete
    string val;
    StrMsg( string val ) : val( val ) {}
};
_Actor Hello {
    Allocation receive( Message & msg ) {
        Case( StrMsg, msg ) {
            . . . msg_d->val . . .;
        }
        return Finished;  // no delete/destroy but remove from actor system
    }
};
int main() {
    uActor::start();
    Hello hellos[2];        // stack allocate actors and messages
    StrMsg hello( "hello" ), bonjour( "bonjour" );
    hellos[0] | hello;
    hellos[1] | bonjour;
    uActor::stop();
} // DEALLOCATE ACTORS/MESSAGES
```

- One shot actor with single string message (no stopMsg).

5.8.4 Thread Object

- C++ is an object-oriented programming language, which suggests:
  - wrap the thread in an object to leverage all class features
  - use object allocation/deallocation to define thread lifetime rather than control structure

```
                _Task T {            // thread type
                    void main() {...} // thread starts here
                };
COBEGIN         {                    // { int i, j, k; } ???
                    T t;             // create object on stack, start thread
COEND           }                    // wait for thread to finish

START           T * t = new T;       // create thread object on heap, start thread
WAIT            delete t;            // wait for thread to finish
```

- Block-terminate/delete must wait for each task's thread to finish. Why?
- Unusual to:
  - create object in a block and not use it
  - allocate object and immediately delete it.
- Simulate COBEGIN/COEND with **_Task** object by creating type for each statement:

```
int i;                            int main() {
_Task T1 {                            { // COBEGIN
    void main() { i = 1; }                T1 t1; T2 t2; T3 t3; T4 t4;
};                                    } // COEND
_Task T2 {                        }
    void main() { p1(5); }        void p1(...) {
};                                    { // COBEGIN
_Task T3 {                                T5 t5; T6 t6; T7 t7; T8 t8;
    void main() { p2(7); }            } // COEND
};                                }
_Task T4 {
    void main() { p3(9); }
};
```

- Simulate START/WAIT with **_Task** object by creating type for each call:

```
int i;                                   int main() {
_Task T1 {                                   T1 * tp = new T1;    // start T1
    void main() { p(5); }                    ... s1 ...
};                                           T2 * tf = new T2;    // start T2
_Task T2 {                                   ... s2 ...
    int temp;                                delete tp;           // wait for p
    void main() { temp = f(8); }             ... s3 ...
  public:                                    delete tf;           // wait for f
    ~T2() { i = temp; }                      ... s4 ...
};                                       }
```

- Variable i cannot be assigned until tf is deleted, otherwise the value could change in s2/s3.
- Implicit or explicit concurrency?

5.9 Termination Synchronization

- A thread terminates when:
  - it finishes normally
  - it finishes with an error
  - it is killed by its parent (or sibling) (not supported in μC++)
  - because the parent terminates (not supported in μC++)
- Children can continue to exist even after the parent terminates (although this is rare).
  - E.g. sign off and leave child process(es) running
- Synchronizing at termination is possible for independent threads.
- Termination synchronization may be used to perform a final communication.

5.10 Divide-and-Conquer

- Divide-and-conquer is characterized by ability to subdivide work across data ⇒ work can be performed independently on the data.
- Work performed on each data group is identical to work performed on data as whole.
- Taken to extremes, each data item is processed independently, but administration of concurrency becomes greater than cost of work.
- Only termination synchronization is required to know when the work is done
- Partial results are then processed further if necessary.
- Sum rows of a matrix concurrently using concurrent statement:

```
#include <uCobegin.h>
int main() {
    const int rows = 10, cols = 10;
    int matrix[rows][cols], subtotals[rows], total = 0;
    // read matrix
    COFOR( r, 0, rows,
    // for ( int r = 0; r < rows; r += 1 )
        subtotals[r] = 0;  // r is loop number
        for ( int c = 0; c < cols; c += 1 )
            subtotals[r] += matrix[r][c];
    ); // wait for threads
    for ( int r = 0; r < rows; r += 1 ) {
        total += subtotals[r];  // total subtotals
    }
    cout << total << endl;
}
```

	matrix				subtotals
T_0 ∑	23	10	5	7	0
T_1 ∑	-1	6	11	20	0
T_2 ∑	56	-13	6	0	0
T_3 ∑	-2	8	-5	1	0
				total	∑

- COFOR *logically* creates end – start threads, indexed start..end – 1 one per loop body.

- Implicit or explicit concurrency?
- Sum rows of a matrix concurrently using actors:

```
_Actor Adder {
    int * row, cols, & subtotal;        // communication
    Allocation receive( Message & ) { // only startMsg
        subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
        return Delete;                  // delete actor (match new)
    }
  public:
    Adder( int row[ ], int cols, int & subtotal ) :
        row( row ), cols( cols ), subtotal( subtotal ) {}
};

int main() {
    . . . // same
    uActor::start();                    // start actor system
    for ( int r = 0; r < rows; r += 1 ) { // actor per row
        *new Adder( matrix[r], cols, subtotals[r] ) | uActor::startMsg;
    }
    uActor::stop();                     // wait for all actors to terminate
    . . . // same
} // main
```

- Sum rows of a matrix concurrently using concurrent objects:

```
_Task Adder {
    int * row, cols, & subtotal;        // communication
    void main() {
        subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
    }
  public:
    Adder( int row[ ], int cols, int & subtotal ) :
        row( row ), cols( cols ), subtotal( subtotal ) {}
};

int main() {
    . . . // same
    Adder * adders[rows];
    for ( int r = 0; r < rows; r += 1 ) { // start threads to sum rows
        adders[r] = new Adder( matrix[r], cols, subtotals[r] );
    }
    for ( int r = 0; r < rows; r += 1 ) { // wait for threads to finish
        delete adders[r];
        total += subtotals[r];          // total subtotals
    }
    cout << total << endl;
}
```

```
int main() {
    . . . // same
    {
        uArrayPtr( Adder, adders, rows );
        for ( int r = 0; r < rows; r += 1 ) { // start threads to sum rows
            adders[r]( matrix[r], cols, subtotals[r] );
        }
    } // wait for tasks to terminate
    for ( int r = 0; r < rows; r += 1 ) {
        total += subtotals[r];  // total subtotals
    }
}
```

- Why create tasks in the heap versus uArray(Adder, adders, rows)?
- Does it matter in what order adder tasks are created?
- Does it matter in what order adder tasks are deleted? (critical path)

5.11 Exceptions

- Exceptions can be handled locally within a task, or nonlocally among coroutines, or concurrently among tasks.
    - All concurrent exceptions are nonlocal, but nonlocal exceptions can also be sequential.
- Local task exceptions are different for coroutines and tasks.
    - Unhandled exception goes to coroutine's last resumer and task's joiner.
- Nonlocal exceptions are possible because each coroutine/task has its own stack (execution state)
- Nonlocal exceptions between a task and a coroutine are the same as between coroutines (single thread).
- Concurrent exceptions among tasks are more complex due to the multiple threads.
- A concurrent exception provides an additional kind of communication among tasks.
- For example, two tasks may begin searching for a key in different sets:

```
_Exception StopEvent {};
_Task Searcher {
    Searcher * partner;
    void main() {
        try {
            _Enable {                   // allow nonlocal exceptions
                . . .                   // search
                if ( key == . . . ) {   // found result
                    _Resume StopEvent() _At *partner; // stop partner
                    _Throw StopEvent(); // stop me
                }
            }
        } catch( StopEvent ) {. . .}    // reset for next search
```

- When one task finds the key, it informs the other task to stop searching.
- For a concurrent raise, the source execution may only block while queueing the event for delivery at the faulting execution.
- After event is delivered, faulting execution it is not interrupted, it polls:
  - when an **_Enable** statement begins/ends,
  - after a call to suspend/resume,
  - after a call to yield,
  - after a call to **_Accept** unblocks for RendezvousFailure.
- Similar to coroutines, see Section 3.7, p. 40, an unhandled exception for a task raises the nonlocal exception uBaseCoroutine::UnhandledException at the task's ***joiner*** and then terminates the task.

```
_Exception E {};
_Task T {
    void main() { _Throw E(); } // unwind
};
int main() {
    try {
        { // extra block
            T t;
        } // continue _CatchResume
    } _CatchResume( uBaseCoroutine::UnhandledException & ) {. . .} // one of
      catch( uBaseCoroutine::UnhandledException & ) {. . .}
    // catch continues after try
}
```

- Forwarding of UnhandledException occurs across any number of tasks (and coroutines), until the program main forwards and the program terminates by calling main's set_terminate.

5.12 Synchronization and Communication During Execution

- Synchronization occurs when one thread waits until another thread has reached a certain execution point (state and code).
- One place synchronization is needed is in transmitting data between threads.
  - One thread has to be ready to transmit the information and the other has to be ready to receive it, simultaneously.
  - Otherwise one might transmit when no one is receiving, or one might receive when nothing is transmitted.

```
bool Insert = false, Remove = false;
int Data;

_Task Prod {
    int N;
    void main() {
        for ( int i = 1; i <= N; i += 1 ) {
            Data = i;   // transfer data
            Insert = true;
            while ( ! Remove ) {} // busy wait
            Remove = false;
        }
    }
  public:
    Prod( int N ) : N( N ) {}
};
```

```
_Task Cons {
    int N;
    void main() {
        int data;
        for ( int i = 1; i <= N; i += 1 ) {
            while ( ! Insert ) {} // busy wait
            Insert = false;
            data = Data; // remove data
            Remove = true;
        }
    }
  public:
    Cons( int N ) : N( N ) {}
};
int main() {
    Prod prod( 5 ); Cons cons( 5 );
}
```

- 2 infinite loops! No, because of implicit switching between threads.
- cons synchronizes (waits) until prod transfers some data, then prod waits for cons to remove the data.
- A loop waiting for an event among threads is called a **busy wait**.
- Are 2 synchronization flags necessary?

5.13 Communication

- Once threads are synchronized there are many ways that information can be transferred from one thread to the other.
- If the threads are in the same memory, then information can be transferred by value or address (e.g., reference parameter).
- If the threads are not in the same memory (distributed), then transferring information by value is straightforward but by address is difficult.

5.14 Critical Section

- Threads may access non-concurrent objects, like a file or linked-list.
- There is a potential problem if there are multiple threads attempting to operate on the same object simultaneously.
- Not a problem if the operation on the object is **atomic** (not divisible).
- This means no other thread can modify any partial results during the operation on the object (but the thread can be interrupted).
- Where an operation is composed of many instructions, it is often necessary to make the operation atomic.
- A group of instructions on an associated object (data) that must be performed atomically is called a **critical section**.
- Preventing simultaneous execution of a critical section by multiple threads is called **mutual exclusion**.
- Must determine when concurrent access is allowed and when it must be prevented.
- One way to handle this is to detect any sharing and serialize all access; wasteful if threads are only reading.
- Improve by differentiating between reading and writing
  - allow multiple readers or a single writer; still wasteful as a writer may only write at the end of its usage.
- **Need to minimize the amount of mutual exclusion (i.e., make critical sections as small as possible, Amdahl's law) to maximize concurrency.**

5.15 Static Variables

- **Warning**: static variables in a class are shared among all objects generated by that class.
- These shared variables may need mutual exclusion for correct usage.
- However, a few special cases where **static** variables can be used safely, e.g., task constructor.
- If task objects are generated serially, **static** variables can be used in the constructor.
- E.g., assigning each task is own name:

```
_Task T {
    static int tid;
    string name; // must supply storage
    . . .
  public:
    T() {
        name = "T" + to_string( tid );  // shared read
        setName( name.c_str() );        // name task
        tid += 1;                        // shared write
    }
    . . .
};
int T::tid = 0;     // initialize static variable in .C file
T t[10];            // 10 tasks with individual names
```

- Task constructor is executed by the creating thread, so array constructors executed sequentially.
- This approach only works if one task creates all the objects and initialization data is internal.
- Instead of **static** variables, pass a task identifier to the constructor:

```
T::T( int tid ) { . . . } // constructor naming
T * t[10];                                   uArray( T, t, 10 );
for ( int i = 0; i < 10; i += 1 ) {          for ( int i = 0; i < 10; i += 1 ) {
    t[i] = new T( i ); // individual names        t[i]( i );
}                                            }
```

- In general, it is best to avoid using shared **static** variables in a concurrent program.

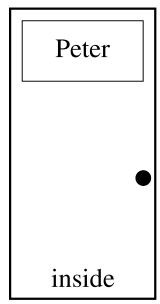
5.16 Mutual Exclusion Game

- Is it possible to write code guaranteeing a statement (or group of statements) is always serially executed by 2 threads?
- Rules of the Game:
  1. Only one thread can be in a critical section at a time with respect to a particular object (**safety**).
  2. Threads may run at arbitrary speed and in arbitrary order, while the underlying system guarantees a thread makes progress (i.e., threads get some CPU time).
  3. If a thread is not in the entry or exit code controlling access to the critical section, it may not prevent other threads from entering the critical section.
  4. In selecting a thread for entry to a critical section, a selection cannot be postponed indefinitely (**liveness**). *Not* satisfying this rule is called **indefinite postponement** or **livelock**.
  5. After a thread starts entry to the critical section, it must eventually enter. *Not* satisfying this rule is called **starvation**.

- **Indefinite postponement and starvation are related by busy waiting.**
- Unlike synchronization, looping for an event in mutual exclusion ***must*** ensure eventual progress.
- Threads waiting to enter can be serviced in any order, as long as each thread eventually enters.
- If threads are *not* serviced in first-come first-serve (FCFS) order of arrival, there is a notion of **unfairness**
- Unfairness implies waiting threads are overtaken by arriving threads, called **barging**.

5.17 Self-Testing Critical Section

```
void CriticalSection() {
    static uBaseTask * curr; // shared
    curr = &uThisTask();
    for ( int i = 1; i <= 100; i += 1 ) {
        . . .                            // work
        if ( curr != &uThisTask() ) {    // check
            abort( "interference" );
        }
    }
}
```

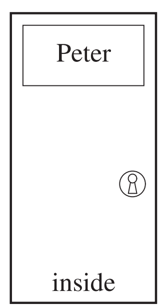


- What is the minimum number of interference tests and where?
- Why are multiple tests useful?

5.18 Software Solutions

5.18.1 Lock

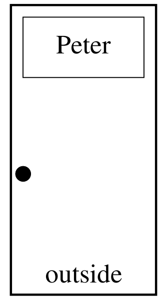
```
enum Yale { CLOSED, OPEN } Lock = OPEN; // shared

_Task PermissionLock {
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            while ( ::Lock == CLOSED ) {} // entry protocol
            ::Lock = CLOSED;
            CriticalSection();      // critical section
            ::Lock = OPEN;          // exit protocol
        }
    }
  public:
    PermissionLock() {}
};
int main() {
    PermissionLock t0, t1;
}
```



Breaks rule 1

5.18.2 Alternation

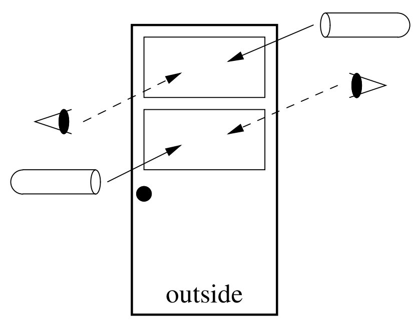
```
int Last = 0;                          // shared

_Task Alternation {
     int me;

     void main() {
          for ( int i = 1; i <= 1000; i += 1 ) {
               while ( ::Last == me ) {} // entry protocol
               CriticalSection();       // critical section
               ::Last = me;             // exit protocol
          }
     }
  public:
     Alternation(int me) : me(me) {}
};
int main() {
     Alternation t0( 0 ), t1( 1 );
}
```



Breaks rule 3

5.18.3 Declare Intent

```
enum Intent { WantIn, DontWantIn };

_Task DeclIntent {
     Intent & me, & you;
     void main() {
          for ( int i = 1; i <= 1000; i += 1 ) {
               me = WantIn;             // entry protocol
               while ( you == WantIn ) {}
               CriticalSection();       // critical section
               me = DontWantIn;         // exit protocol
          }
     }
  public:
     DeclIntent( Intent & me, Intent & you ) :
               me(me), you(you) {}
};
int main() {
     Intent me = DontWantIn, you = DontWantIn;
     DeclIntent t0( me, you ), t1( you, me );
}
```



Breaks rule 4

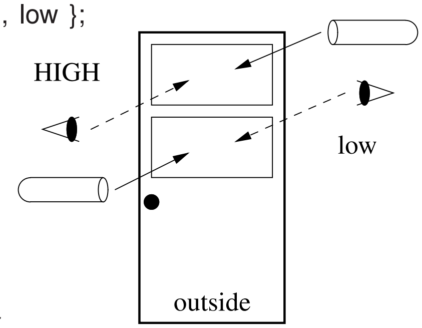
5.18.4 Retract Intent

```
enum Intent { WantIn, DontWantIn };
_Task RetractIntent {
    Intent & me, & you;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                    // entry protocol
                me = WantIn;
              if ( you == DontWantIn ) break;
                me = DontWantIn;
                while ( you == WantIn ) {}
            }
            CriticalSection();              // critical section
            me = DontWantIn;                // exit protocol
        }
    }
  public:
    RetractIntent( Intent & me, Intent & you ) : me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    RetractIntent t0( me, you ), t1( you, me );
}
```

Breaks rule 4

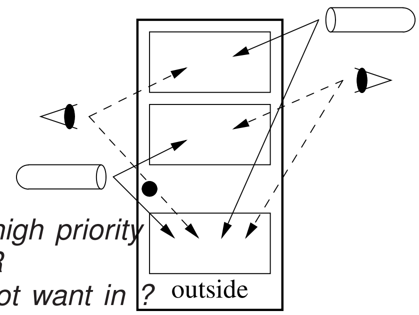
5.18.5 Prioritized Retract Intent

```
enum Intent { WantIn, DontWantIn }; enum Priority { HIGH, low };
_Task PriorityEntry {
    Intent & me, & you;  Priority priority;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                    // entry protocol
                me = WantIn;
              if ( you == DontWantIn ) break;
                if ( priority == low ) {
                    me = DontWantIn;
                    while (you == WantIn) {} // busy wait
                }
            }
            CriticalSection();              // critical section
            me = DontWantIn;                // exit protocol
        }
    }
  public:
    PriorityEntry( Priority p, Intent & me, Intent & you ) : priority(p), me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    PriorityEntry t0( HIGH, me, you ), t1( low, you, me );
} // main
```



Breaks rule 5

5.18.6 Dekker (modified retract intent)




```
enum Intent { WantIn, DontWantIn };
Intent * Last;
_Task Dekker {
    Intent & me, & you;
    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                // entry protocol, high priority
                me = WantIn;            // READ FLICKER
              if ( you == DontWantIn ) break; // does not want in
                if ( ::Last == &me ) { // low priority task ?
                    me = DontWantIn; // retract intent, READ FLICKER
                    while ( ::Last == &me // low priority busy wait
                           && you == WantIn ) {}
                }
            }
            CriticalSection();
            if ( ::Last != &me )        // exit protocol
                ::Last = &me;           // READ FLICKER
            me = DontWantIn;            // READ FLICKER
        }
    }
  public:
    Dekker( Intent & me, Intent & you ) : me(me), you(you) {}
};
int main() {
    Intent me = DontWantIn, you = DontWantIn;
    ::Last = &me;           // arbitrary who starts as last
    Dekker t0( me, you ), t1( you, me );
}
```

- Dekker's algorithm appears **RW-safe**.
    - On cheap multi-core computers, read/write is not atomic.
    - Hence, simultaneous writes scramble bits, and for simultaneous read/write, read sees flickering bits during write.
    - RW-safe means a mutual-exclusion algorithm works for non-atomic read/write.
    - Dekker has no simultaneous W/W because intent reset *after* alternation in exit protocol.
    - Dekker has simultaneous R/W but all are equality so works ***if final value never flickers***.
- 2015 Hesselink found two failure case if values flickers:

1.

T_0	T_1
9 ::Last = &me	
10 me = DontWantIn	
(flicker DontWantIn)	
	3 you == DontWantIn (**true**)
	7 Critical Section
	9 ::Last = &me
(flicker WantIn)	
	3 you == DontWantIn (**false**)
	4 ::Last == &me (**true**)
	6 low priority wait
(flicker DontWantIn)	
terminate	
	6 ::Last == &me (**true**, spin forever)

T_1 spins forever (break rule 4)

2.

T_0	T_1
7 Critical Section	
9 ::Last = &me	
(flicker you T_1)	
	6 ::Last == &me && you == WantIn (**true**)
(flicker me T_0)	
10 me = DontWantIn	
(repeat)	(repeat)

T_1 starvation (break rule 5)

- RW-safe version (**Hesselink**)
  - line 6: add conjunction you == WantIn
    ⇒ stop spinning
  - line 8: add conditional assignment to ::Last
    ⇒ not assigning at line 9 when ::Last != &me prevents flicker so T_1 makes progress.
- Dekker has **unbounded overtaking** (not starvation) because *race loser retracts intent*.
- ⇒ thread exiting critical does not exclude itself for reentry.
  - T0 exits critical section and attempts reentry
  - T1 is now high priority (Last != me) but delays in low-priority busy-loop and resetting its intent.
  - T0 can enter critical section unbounded times until T1 resets its intent
  - T1 sets intent ⇒ bound of 1 as T0 can be entering or in critical section
- Unbounded overtaking is allowed by rule 3: not preventing entry to the critical section by the delayed thread.

5.18.7 Peterson (modified declare intent)

```
enum Intent { WantIn, DontWantIn };
Intent * Last;

_Task Peterson {
     Intent & me, & you;
     void main() {
          for ( int i = 1; i <= 1000; i += 1 ) {
1              me = WantIn;              // entry protocol, order matters
2              ::Last = &me;             // RACE!
3              while ( you == WantIn && ::Last == &me ) {}
4              CriticalSection();        // critical section
5              me = DontWantIn;          // exit protocol
          }
     }
  public:
     Peterson( Intent & me, Intent & you ) : me(me), you(you) {}
};
int main() {
     Intent me = DontWantIn, you = DontWantIn;
     Peterson t0(me, you), t1(you, me);
}
```

- Peterson's algorithm is RW-**unsafe** requiring atomic read/write operations.
- Peterson has **bounded overtaking** because *race loser does not retracts intent*.
- ⇒ thread exiting critical excludes itself for reentry.
  - T0 exits critical section and attempts reentry
  - T0 runs race by itself and loses
  - T0 must wait (Last == me)
  - T1 eventually sees (Last != me)
- Bounded overtaking is allowed by rule 3 because the prevention is occurring *in the entry protocol*.
- Can line 2 be moved before 1?

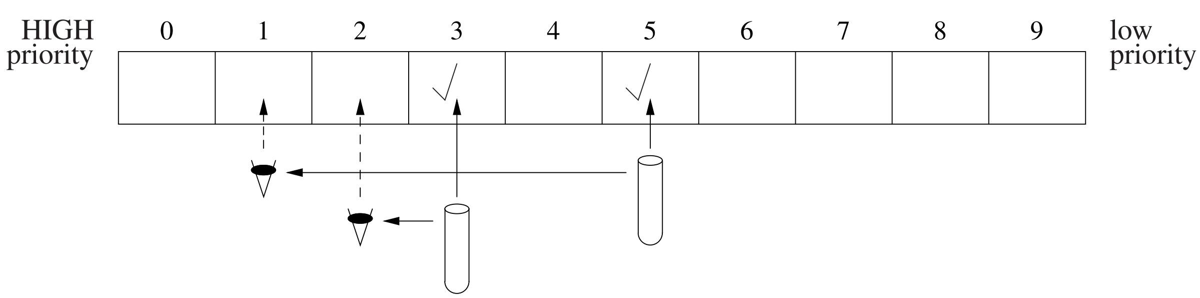
```
1  2  ::Last = &me;             // RACE!
2  1  me = WantIn;              // entry protocol
3  3  while ( you == WantIn && ::Last == &me ) {}
4  4  CriticalSection();        // critical section
5  5  me = DontWantIn;          // exit protocol
```

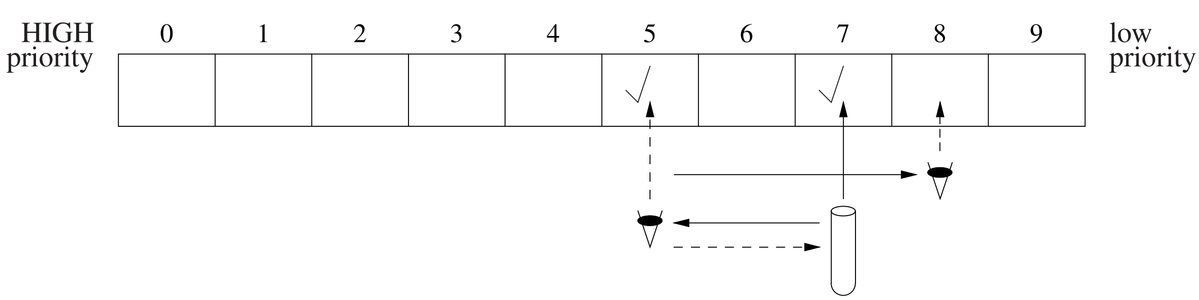
  - T0 executes Line 1 ⇒ ::Last = T0
  - T1 executes Line 1 ⇒ ::Last = T1
  - T1 executes Line 2 ⇒ T1 = WantIn
  - T1 enters CS, because T0 == DontWantIn
  - T0 executes Line 2 ⇒ T0 = WantIn
  - T0 enters CS, because ::Last == T1

5.18.8 N-Thread Prioritized Entry

```
enum Intent { WantIn, DontWantIn };
_Task NTask { // Lamport (simpler version of Burns-Lynch)
    Intent * intents;                     // position & priority
    int N, priority, i, j;
    void main() {
        for ( i = 1; i <= 1000; i += 1 ) {
            // step 1, wait for tasks with higher priority
            do {                          // entry protocol
                intents[priority] = WantIn;
                // check if task with higher priority wants in
                for ( j = priority-1; j >= 0; j -= 1 ) {
                  if ( intents[j] == WantIn ) {
                        intents[priority] = DontWantIn;
                        while ( intents[j] == WantIn ) {}
                        break;
                    }
                }
            } while ( intents[priority] == DontWantIn );
            // step 2, wait for tasks with lower priority
            for ( j = priority+1; j < N; j += 1 ) {
                while ( intents[j] == WantIn ) {}
            }
            CriticalSection();
            intents[priority] = DontWantIn;       // exit protocol
        }
    }
  public:
    NTask( Intent i[ ], int N, int p ) : intents(i), N(N), priority(p) {}
};
```

Breaks rule 5





- Only N bits needed.

- No known solution for all 5 rules using only N bits.
- Other N-thread solutions use more memory.
(best: 3-bit RW-unsafe, 4-bit RW-safe).

5.18.9 N-Thread Bakery (Tickets)

```
_Task Bakery { // (Lamport) Hehner-Shyamasundar
    int * ticket, N, priority;
    void main() {
        for ( int i = 0; i < 1000; i += 1 ) {
            // step 1, select a ticket
            ticket[priority] = 0;           // highest priority
            int max = 0;                    // O(N) search
            for ( int j = 0; j < N; j += 1 ) { //  for largest ticket
                int v = ticket[j];          // can change so copy
                if ( v != INT_MAX && max < v ) max = v;
            }
            max += 1;                       // advance ticket
            ticket[priority] = max;
            // step 2, wait for ticket to be selected
            for ( int j = 0; j < N; j += 1 ) { // check tickets
                while ( ticket[j] < max ||
                  (ticket[j] == max && j < priority) ) {}
            }
            CriticalSection();
            ticket[priority] = INT_MAX;     // exit protocol
        }
    }
  public:
    Bakery( int t[ ], int N, int p ) : ticket(t), N(N), priority(p) {}
};
```

HIGH priority	0	1	2	3	4	5	6	7	8	9	low priority
	∞	∞	17	∞	0	18	18	0	20	19	

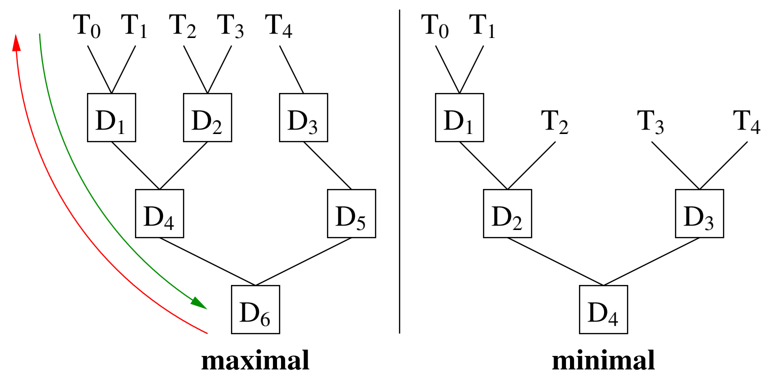
- ticket value of ∞ (INT_MAX) ⇒ don't want in
- ticket value of **0** ⇒ selecting ticket
- ticket selection is unusual
- tickets are not unique ⇒ use position as secondary priority
- low ticket and position ⇒ high priority
- ticket values cannot increase indefinitely ⇒ could fail (probabilistically correct)
- ticket value reset to INT_MAX when no attempted entry
- NM bits, where M is the ticket size (e.g., 32 bits)

- Lamport RW-safe
- Hehner/Shyamasundar RW-unsafe

  assignment ticket[priority] = max can flickers to INT_MAX ⇒ other tasks proceed

5.18.10 Tournament

- Binary (d-ary) tree with $\lceil N/2 \rceil$ start nodes and $\lceil \lg N \rceil$ levels.



- Thread assigned to start node, where it begins mutual exclusion process.
- Each node is like a Dekker or Peterson 2-thread algorithm.
- Tree structure tries to find compromise between fairness and performance.
- Exit protocol must retract intents in ***reverse*** order.
- Otherwise race between retracting/released threads along same tree path:
  - T_0 retracts its intent (left) at D_1,
  - T_1 (right) now moves from D_1 to D_4, sets its intent at D_4 (left), and with no competition at D_4 proceeds to D_6 (left),
  - T_0 (left) now retracts the intent at D_4 set by T_1,
  - $T_{2/3}$ continue from D_2, sets its intent at D_4 (right), and with no competition at D_4 (left) proceeds to D_6, which ultimately violates mutual exclusion.
- No overall livelock because each node has no livelock.
- No starvation because each node guarantees progress, so each thread eventually reaches the root.
- Tournament algorithm RW-safety depends on MX algorithm; tree traversal is local to each thread.
- Tournament algorithms have unbounded overtaking as no synchronization among the nodes of the tree.

- For a minimal binary tree, the tournament approach uses $(N-1)M$ bits, where $(N-1)$ is the number of tree nodes and M is the node size (e.g., intent, turn).

```
_Task TournamentMax { // Taubenfeld-Buhr
    struct Token { int intents[2], turn; };     // intents/turn
    static Token ** t;                          // triangular matrix
    int depth, id;

    void main() {
        unsigned int lid;                       // local id at each tree level
        for ( int i = 0; i < 1000; i += 1 ) {
            lid = id;                           // entry protocol
            for ( int lv = 0; lv < depth; lv += 1 ) {
                binary_prologue( lid & 1, &t[lv][lid >> 1] );
                lid >>= 1;                      // advance local id for next tree level
            }
            CriticalSection( id );
            for ( int lv = depth - 1; lv >= 0; lv -= 1 ) { // exit protocol
                lid = id >> lv;                 // retract reverse order
                binary_epilogue( lid & 1, &t[lv][lid >> 1] );
            }
        }
    }
  public:
    TournamentMax( struct Token * t[ ], int depth, int id ) :
        t( t ), depth( depth ), id( id ) {}
};
```

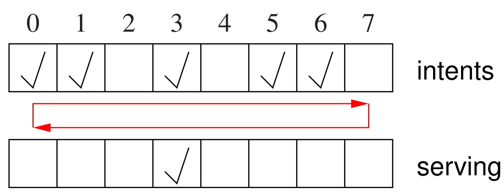
- Can be optimized to 3 shifts and exclusive-or using Peterson 2-thread for binary.
- Path from leaf to root is fixed per thread ⇒ table lookup possible using max or min tree.

5.18.11 Arbiter

- Create full-time arbitrator task to control entry to critical section.

```
bool intents[N], serving[N];            // initialize to false

_Task Client {
    int me;
    void main() {
        for ( int i = 0; i < 100; i += 1 ) {
            intents[me] = true;         // entry protocol
            while ( ! serving[me] ) {} // busy wait
            CriticalSection();
            serving[me] = false;        // exit protocol
        }
    }
  public:
    Client( int me ) : me( me ) {}
};
```

```
_Task Arbiter {
    void main() {
        int i = N;                      // force cycle to start at id=0
        for ( ;; ) {
            do {                        // circular search => no starvation
                i = (i + 1) % N;        // advance next client
            } while ( ! intents[i] );   // not want in ?
            intents[i] = false;         // retract intent on behalf of client
            serving[i] = true;          // wait for exit from critical section
            while ( serving[i] ) {}     // busy wait
        }
    }
};
```



- Mutual exclusion becomes synchronization between arbiter and clients.
- Arbiter never uses the critical section ⇒ no indefinite postponement.
- Arbiter cycles through waiting clients (not FCFS) ⇒ no starvation.
- RW-unsafe due to read flicker.
- Cost is creation, management, and execution (continuous busy waiting) of arbiter task.

5.19 Hardware Solutions

- Software solutions to the critical-section problem rely on
  - shared information,
  - communication among threads,
  - (maybe) atomic memory-access.
- Hardware solutions introduce level below software level.
- Cheat by making assumptions about execution impossible at software level.

  E.g., control order and speed of execution.
- Allows elimination of much of the shared information and the checking of this information required in the software solution.
- Special instructions to perform an **atomic read and write operation**.
- Sufficient for multitasking on a single CPU.

5.19.1 Test/Set Instruction

- Simple lock of critical section fails:

```
int Lock = OPEN;             // shared
// each task does
while ( Lock == CLOSED );    // fails to achieve (read)
Lock = CLOSED;               // mutual exclusion (write)
// critical section
Lock = OPEN;
```

- The test-and-set instruction performs an atomic read and fixed assignment.

```
int Lock = OPEN; // shared

int TestSet( int & b ) {     | void Task::main() { // each task does
    // begin atomic          |     while( TestSet( Lock ) == CLOSED );
    int temp = b;            |     // critical section
    b = CLOSED;              |     Lock = OPEN;
    // end atomic            | }
    return temp;             |
}                            |
```

  - if test/set returns open ⇒ loop stops and lock is set to closed
  - if test/set returns closed ⇒ loop executes until the other thread sets lock to open

- Works for N threads attempting entry to critical section and only depends on one shared datum (lock).
- However, rule 5 is broken, as there is no guarantee of eventual progress.
- In multiple CPU case, hardware (bus) must also guarantee multiple CPUs cannot interleave these special R/W instructions on same memory location.

5.19.2 Swap Instruction

- The swap instruction performs an atomic interchange of two separate values.

```
int Lock = OPEN; // shared

void Swap( int & a, & b ) {  | void Task::main() { // each task does
    int temp;                |     int dummy = CLOSED;
    // begin atomic          |     do {
    temp = a;                |         Swap( Lock, dummy );
    a = b;                   |     } while( dummy == CLOSED );
    b = temp;                |     // critical section
    // end atomic            |     Lock = OPEN;
}                            | }
```

  - if dummy returns open ⇒ loop stops and lock is set to closed
  - if dummy returns closed ⇒ loop executes until the other thread sets lock to open

5.19.3 Fetch and Increment Instruction

- The fetch-and-increment instruction performs an increment between the read and write.

```
int Lock = 0; // shared
```

```
int FetchInc( int & val ) {
    // begin atomic
    int temp = val;
    val += 1;
    // end atomic
    return temp;
}
```

```
void Task::main() { // each task does
    while ( FetchInc( Lock ) != 0 );
    // critical section
    Lock = 0;
```

- Often fetch-and-increment is generalized to add any value ⇒ also decrement with negative value.

- Lock counter can overflow during busy waiting and starvation (rule 5).

- Use ticket counter to solve both problems (Bakery Algorithm, see Section 5.18.9, p. 93):

```
class ticketLock {
    unsigned int tickets, serving;
  public:
    ticketLock() : tickets( 0 ), serving( 0 ) {}
    void acquire() {                                 // entry protocol
        int ticket = FetchInc( tickets );            // obtain a ticket
        while ( ticket != serving ) {}               // busy wait
    }
    void release() {                                 // exit protocol
        serving += 1;
    }
};
```

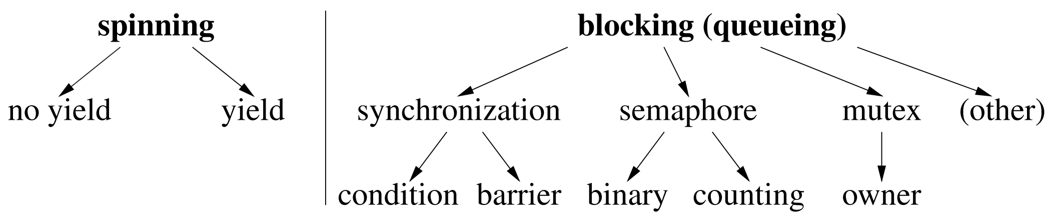
- Ticket overflow is a problem only if all values used simultaneously, and FIFO service ⇒ no starvation.

6 Locks

- Package software/hardware locking into abstract type for general use.
- Locks are constructed for synchronization or mutual exclusion or both.

6.1 Lock Taxonomy

- Lock implementation is divided into two general categories: spinning and blocking.



- Spinning locks busy wait until an event occurs ⇒ task oscillates between ready and running states due to time slicing.
- Blocking locks do not busy wait, but block until an event occurs ⇒ **some *other* mechanism must unblock waiting task when the event happens**.
- Within each category, different kinds of spinning and blocking locks exist.

6.2 Spin Lock

- A **spin lock** is implemented using busy waiting, which loops checking for an event to occur.

```
while( TestSet( Lock ) == CLOSED );  // use up time-slice (no yield)
```

- So far, when a task is busy waiting, it loops until:
  - critical section becomes unlocked or an event happens.
  - waiting task is preempted (time-slice ends) and put back on ready queue.

  Hence, CPU is wasting time constantly checking the event.
- To increase uniprocessor efficiency, a task can:
  - explicitly terminate its time-slice
  - move back to the ready state after only ***one*** event-check fails. (Why one?)
- Task member yield relinquishes time-slice by *rescheduling* running task back onto ready queue.

```
while( TestSet( Lock ) == CLOSED ) uThisTask().yield(); // relinquish time-slice
```

- To increase multiprocessor efficiency, a task can yield after N event-checks fail. (Why N?)

- Some spin-locks allow adjustment of spin duration, called **adaptive spin-lock**.
- Most spin-lock implementations break rule 5, i.e., no bound on service. ⇒ possible starvation of one or more tasks.
- Spin lock is appropriate and necessary in situations where there is no other work to do.

6.2.1 Implementation

- μC++ provides a non-yielding spin lock, uSpinLock, and a yielding spin lock, uLock.

```
class uSpinLock {
  public:
    uSpinLock(); // open
    void acquire();
    bool tryacquire();
    void release();
};
```

```
class uLock {
  public:
    uLock( unsigned int value = 1 );
    void acquire();
    bool tryacquire();
    void release();
};
```

- Both locks are built directly from an atomic hardware instruction.
- Lock starts closed (0) or opened (1); waiting tasks compete to acquire lock after release.
- In theory, starvation could occur; in practice, it is seldom a problem.
- tryacquire makes one attempt to acquire the lock, i.e., it does not wait.
- It is *not* meaningful to read or to assign to a lock variable, or copy a lock variable, e.g., pass it as a value parameter.
- synchronization

```
_Task T1 {
    uLock & lk;
    void main() {
        . . .
        S1
        lk.release();
        . . .
    }
  public:
    T1( uLock & lk ) : lk(lk) {}
};
int main() {
    uLock lock( 0 ); // closed
    T1 t1( lock );
    T2 t2( lock );
}
```

```
_Task T2 {
    uLock & lk;
    void main() {
        . . .
        lk.acquire();
        S2
        . . .
    }
  public:
    T2( uLock & lk ) : lk(lk) {}
};
```

- mutual exclusion

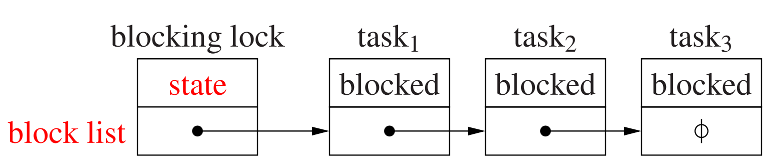
```
_Task T {
    uLock & lk;
    void main() {
        . . .
        lk.acquire();
        // critical section
        lk.release();
        . . .
        lk.acquire();
        // critical section
        lk.release();
        . . .
    }
  public:
    T( uLock & lk ) : lk(lk) {}
};
```

```
int main() {
    uLock lock( 1 ); // open
    T t0( lock ), t1( lock );
}
```

  - Does this solution afford maximum concurrency?
  - Depends on critical sections: **independent** (disjoint) or **dependent**.
  - How many locks are needed for mutual exclusion?

6.3 Blocking Locks

- For spinning locks,
  - acquiring task(s) is solely responsible for detecting an open lock after the releasing task opens it.
- For blocking locks,
  - acquiring task makes ***one*** check for open lock and blocks
  - releasing task has sole responsibility for detecting blocked acquirer and transferring lock, or just releasing lock.
- Blocking locks reduce busy waiting by having releasing task do additional work: **cooperation**.
  - What advantage does the releasing task get from doing the cooperation?
- Therefore, all blocking locks have
  - state to facilitate lock semantics
  - list of blocked acquirers



- Which task is scheduled next from the list of blocked tasks?

6.3.1 Mutex Lock

- **Mutex lock** is used solely to provide mutual exclusion.
- Restricting a lock to just mutual exclusion:
  - separates lock usage between synchronization and mutual exclusion
  - permits optimizations and checks as the lock only provides one specialized function
- Mutex locks are divided into two kinds:
  - **single acquisition** : task that acquired the lock cannot acquire it again
  - **multiple acquisition** : lock owner can acquire it multiple times, called an **owner lock**
- Multiple acquisition can handle looping or recursion involving a lock:

```
void f() {
    . . .
    lock.acquire();
    . . . f();          // recursive call within critical section
    lock.release();
}
```

- May require only one release to unlock, or as many releases as acquires.

6.3.1.1 Implementation

- Multiple acquisition lock manages owner state (**blue**).

```
class MutexLock {
    bool avail;                     // resource available ?
    Task * owner                    // lock owner
    queue<Task> blocked;            // blocked tasks
    SpinLock lock;                  // mutex nonblocking lock

  public:
    MutexLock() : avail( true ), owner( nullptr ) {}
    void acquire() {
        lock.acquire();             // barging
        while ( ! avail && owner != currThread() ) { // busy waiting
            // add self to lock' s blocked list
            yieldNoSchedule();      // do not reschedule to ready queue
            lock.acquire();         // reacquire spinlock
        }
        avail = false;
        owner = currThread();       // set new owner
        lock.release();
    }
```

```
        void release() {
            lock.acquire();
            if ( owner != currThread() ) . . . // ERROR CHECK
            owner = nullptr;           // no owner
            if ( ! blocked.empty() ) {
                // remove task from blocked list and make ready
            }
            avail = true;              // reset
            lock.release();            // RACE
        }
    };
```

- yieldNoSchedule yields the processor time-slice but does not reschedule thread to ready queue.
- Single or multiple unblock for multiple acquisition?
- avail is necessary as queue can be empty but critical section occupied.
- Problem: **blocking occurs holding spin lock!**
- ⇒ release lock before blocking

```
// add self to blocked list of lock
lock.release();          // allow releasing task to unblock next waiting task
// PREEMPTION ⇒ put on ready queue
yieldNoSchedule();
```

- **Race between blocking and unblocking tasks.**
- Blocking task releases spin lock but preempted *before* yield and put onto ready queue.
- Unblocking task can enter, see blocking task on lock's blocked list, and put on ready queue.
- But task is still on the ready queue because of the preemption!
- Need ***magic*** to atomically yield without scheduling ***and*** release spin lock.
- Magic is often accomplished with more cooperation:

```
yieldNoSchedule( lock );
```

- Spin lock is passed to the runtime system, which does the yield without schedule and then, on behalf of the user thread, unlocks the lock.
- Alternative approach is park/unpark, where each thread blocks on a private binary semaphore (see Section 6.4.4.6, p. 132 private semaphore).
- Disabling and enabling interrupts is too expense.
- Note, the runtime system violates order and speed of execution by being non-preemptable.

- Problem: avail and lock reset ⇒ acquiring tasks can **barge** ahead of released task.
- Released task must check again (**while**) ⇒ busy waiting ⇒ starvation
- **Barging avoidance** (cooperation): hold avail between releasing and unblocking task (bounded overtaking).

```
void acquire() {
    lock.acquire();              // barging
    if ( ! avail && owner != currThread() ) { // avoid barging
        // add self to lock' s blocked list
        yieldNoSchedule( lock );
        // DO NOT REACQUIRE LOCK, avail == false
    } else {
        avail = false;
        lock.release();
    }
    owner = currThread();    // set new owner, safe as avail == false
}

void release() {
    lock.acquire();
    owner = nullptr;             // no owner
    if ( ! blocked.empty() ) {
        // remove task from blocked list and make ready
    } else {
        avail = true;            // conditional reset
    }
    lock.release();              // RACE
}
```

- Bargers enter mutual-exclusion protocol but block so released task does not busy wait (**if** rather than **while**).
- Mutual exclusion is ***conceptually passed*** from releasing to unblocking tasks (baton passing).
- **Barging prevention** (cooperation): hold lock between releasing and unblocking task (unbounded overtaking).

```
void acquire() {
    lock.acquire();              // prevention barging
    if ( ! avail && owner != currThread() ) {
        // add self to lock' s blocked list
        yieldNoSchedule( lock );
        // DO NOT REACQUIRE LOCK
    } else avail = false;
    owner = currThread();    // set new owner
    lock.release();
}
```

```
    void release() {
        lock.acquire();
        owner = nullptr;          // no owner
        if ( ! blocked.empty() ) {
            // remove task from blocked list and make ready
            // DO NOT RELEASE LOCK
        } else {
            avail = true;         // conditional reset
            lock.release();       // NO RACE
        }
    }
```

- **Critical section is not bracketeted by the spin lock when lock is passed.**
- Alternative (cooperation): leave lock owner at front of blocked list to act as availability and owner variable.

```
class MutexLock {
    queue<Task> blocked;          // blocked tasks
    SpinLock lock;                // nonblocking lock
  public:
    void acquire() {
        lock.acquire();           // prevention barging
        if ( blocked.empty() ) {  // no one waiting ?
            node.owner = currThread();
            // add self to lock's blocked list
        } else if ( blocked.head().owner != currThread() ) { // not owner ?
            // add self to lock′ s blocked list
            yieldNoSchedule( lock );
            // DO NOT REACQUIRE LOCK
        }
        lock.release();
    }
    void release() {
        lock.acquire();
        // REMOVE TASK FROM HEAD OF BLOCKED LIST
        if ( ! blocked.empty() ) {
            // MAKE TASK AT FRONT READY BUT DO NOT REMOVE
            // DO NOT RELEASE LOCK
        } else {
            lock.release();       // NO RACE
        }
    }
};
```

- If critical section acquired, blocked list must have a node on it to check for in-use.

6.3.1.2 uOwnerLock

- μC++ provides a multiple-acquisition mutex-lock, uOwnerLock:

```
class uOwnerLock {
  public:
    uOwnerLock();
    uBaseTask * owner();
    unsigned int times();
    void acquire();
    bool tryacquire();
    void release();
};
```

- owner() returns **nullptr** if no owner, otherwise address of task that currently owns lock.
- times() returns number of times lock has been acquired by owner task.
- Must release as many times as acquire.
- Otherwise, operations same as for uLock but with blocking instead of spinning for acquire.

6.3.1.3 Mutex-Lock Release-Pattern

- To ensure a mutual exclusion lock is always released use the following patterns.
  - executable statement – finally clause

```
uOwnerLock lock;
lock.acquire();
try {
    . . .                     // protected by lock
} _Finally {
    lock.release();
}
```

  - allocation/deallocation (RAII – Resource Acquisition Is Initialization)

```
class RAII {                  // create once
    uOwnerLock & lock;
  public:
    RAII( uOwnerLock & lock ) : lock( lock ) { lock.acquire(); }
    ~RAII() { lock.release(); }
};
uOwnerLock lock;
{
    RAII raii( lock );        // lock acquired by constructor
    . . .                     // protected by lock
}                             // lock release by destructor
```

- Lock always released on normal, local transfer (**break**/**return**), and exception.
- Cannot be used for barging prevention. Why?

6.3.1.4 Stream Locks

- Specialized mutex lock for I/O based on uOwnerLock.
- Concurrent use of C++ streams can produce unpredictable results.
  - if two tasks execute:

    ```
    task1 : cout << "abc " << "def " << endl;
    task2 : cout << "uvw " << "xyz " << endl;
    ```

    any of the outputs can appear:

abc def uvw xyz	abc uvw xyz def	uvw abc xyz def	abuvwc dexf yz	uvw abc def xyz

- μC++ provides: osacquire for output streams and isacquire for input streams.
- Most common usage is to create an anonymous stream lock for a cascaded I/O expression:

  ```
  task1 : osacquire( cout ) << "abc " << "def " << endl;
  task2 : osacquire( cout ) << "uvw " << "xyz " << endl;
  ```

  constraining the output to two different lines in either order:

abc def uvw xyz	uvw xyz abc def

- Multiple I/O statements can be protected using block structure:

  ```
  {   // acquire the lock for stream cout for block duration
      osacquire acq( cout ); // named stream lock
      cout << "abc";
      osacquire( cout ) << "uvw " << "xyz " << endl; // OK?
      cout << "def";
  }   // implicitly release the lock when "acq" is deallocated
  ```

- Which *locking-release* pattern is used by stream locks?

6.3.2 Synchronization Lock

- **Synchronization lock** is used solely to block tasks waiting for synchronization.
- Weakest form of blocking lock as its only state is list of blocked tasks.
  - ⇒ ***acquiring task always blocks*** (no state to make it conditional)

    Need ability to yield time-slice and block versus yield and go back on ready queue.
  - ⇒ ***release is lost when no waiting task*** (no state to remember it)
- Often called a **condition lock**, with wait / signal(notify) for acquire / release.

6.3.2.1 Implementation

- Like mutex lock, synchronization lock needs mutual exclusion for safe implementation.
- Location of mutual exclusion classifies synchronization lock:

  external locking use an external lock to protect task list,

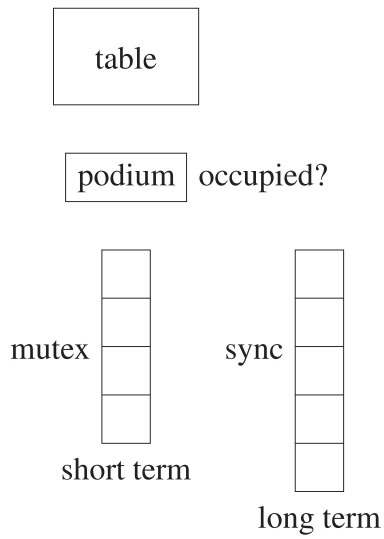
  internal locking use an internal lock to protect state (lock is extra state).

- external locking

```
class SyncLock {
    Task * list;
  public:
    SyncLock() : list( nullptr ) {}
    void acquire() {
        // add self to task list
        yieldNoSchedule();
    }
    void release() {
        if ( list != nullptr ) {
            // remove task from blocked list and make ready
        }
    }
};
```

  - Use external state to avoid lost release.
  - Need mutual exclusion to protect task list and possible external state.
  - Releasing task detects a blocked task and performs necessary cooperation.

- Usage pattern:
  - Cannot enter a restaurant if all tables are full.
  - Must acquire a lock to check for an empty table because state can change.
  - If no free table, block on waiting-list until a table becomes available or **leave** (balk) and eat somewhere else.



- Why is a single waiting queue (bench) inadequate?

```
// shared variables
    MutexLock m;              // external mutex lock
    SyncLock s;               // synchronization lock
    bool occupied = false;    // indicate if event has occurred
// acquiring task
    m.acquire();              // mutual exclusion to examine state & possibly block
    if ( occupied ) {         // event not occurred ?
        if ( /* do not wait */ ) { m.release(); /* go elsewhere */ }
        s.acquire();          // long-term block for event
        m.acquire();          // require mutual exclusion to set state
    }
    occupied = true;          // set
    m.release();
... EAT! ...
// releasing task
    m.acquire();              // mutual exclusion to examine state
    occupied = false;         // reset
    s.release();              // possibly unblock waiting task
    m.release();              // release mutual exclusion
```

- **Blocking occurs holding external mutual-exclusion lock!**
- ⇒ release lock before blocking by modifying synchronization-lock acquire.

```
void SyncLock::acquire( MutexLock & m ) { // add parameter
    // add self to task list
    m.release();              // release external mutex-lock
    // PREEMPTION ⇒ put on ready queue
    yieldNoSchedule();
    // possibly reacquire mutexlock
}
```

- **As before, preemption results in race between blocking and unblocking tasks.**
- To prevent race, need to cooperate with scheduler.

```
void SyncLock::acquire( MutexLock & m ) {
    // add self to task list
    yieldNoSchedule( m ); // scheduler unlocks m
    // possibly reacquire mutexlock
}
```

- Or, protecting mutex-lock is bound at synchronization-lock creation and used implicitly.
- Now use first usage pattern.

```
// acquiring task
    m.acquire();              // mutual exclusion to examine state & possibly block
    if ( occupied ) {         // event not occurred ?
        if ( /* do not wait */ ) { m.release(); /* go elsewhere */ }
        s.acquire( m );       // block for event and release mutex lock
        . . .
```

- Has the race been prevented?
- Problem: barging can occur when releasing task resets occupied.
  - ⇒ non-FIFO order and possible starvation
- Note, same problems as inside mutex lock but occurring ***outside*** between mutex and synchronization locks.
- Use barging avoidance:

```
// releasing task
    m.acquire();              // mutual exclusion to examine state
    if ( ! s.empty() ) s.release(); // unblock, no reset
    else occupied = false;    // reset
    m.release();              // release mutual exclusion
```

  or prevention:

```
// releasing task
    m.acquire();              // mutual exclusion to examine state
    if ( ! s.empty() ) s.release(); // unblock, no reset
    else { occupied = false; m.release(); } // reset & release
```

- internal locking

```
class SyncLock {
    Task * list;          // blocked tasks
    SpinLock lock;        // internal lock
  public:
    SyncLock() : list( nullptr ) {}
    void acquire( MutexLock & m ) {  // optional external lock
        lock.acquire();
        // add self to task list
        m.release();      // release external mutex-lock
        CAN BE INTERRUPTED HERE
        yieldNoSchedule( lock );
        m.acquire();      // possibly reacquire after blocking
    }
    void release() {
        lock.acquire();
        if ( list != nullptr ) {
            // remove task from blocked list and make ready
        }
        lock.release();
    }
};
```

- Why does acquire still take an external lock?
- Why is the race after releasing the external mutex-lock not a problem?

- Has the busy wait been removed from the blocking lock?

6.3.2.2 uCondLock

- μC++ provides an internal synchronization-lock, uCondLock.

```
class uCondLock {
  public:
    uCondLock();
    void wait( uOwnerLock & lock );
    bool signal();
    bool broadcast();
    bool empty();
};
```

- wait and signal are used to block a thread on and unblock a thread from the queue of a condition, respectively.
- wait atomically blocks the calling task and **releases argument owner-lock**.
- **wait reacquires its argument owner-lock before returning.**
- signal unblocks a single task in FIFO order.
- broadcast unblocks all waiting tasks.

- signal/broadcast do nothing for an empty condition and return false; otherwise, return true.
- empty returns **false** if blocked tasks on the queue and **true** otherwise.

6.3.2.3 Programming Pattern

- Using synchronization locks is complex because they are weak.
- Must provide external mutual-exclusion and protect against loss signal (release).
- Why is synchronization more complex for blocking locks than spinning (uLock)?

```
bool done = false;
_Task T1 {
    uOwnerLock & mlk;
    uCondLock & clk;

    void main() {
        mlk.acquire(); // prevent lost signal
        if ( ! done )  // signal occurred ?
            // signal not occurred
            clk.wait( mlk ); // atomic wait/release
            // mutex lock re-acquired after wait
        mlk.release(); // release either way
        S2;
    }
  public:
    T1( uOwnerLock & mlk,
        uCondLock & clk ) :
        mlk(mlk), clk(clk) {}
};
```

```
_Task T2 {
    uOwnerLock & mlk;
    uCondLock & clk;

    void main() {
        S1;
        mlk.acquire(); // prevent lost signal
        done = true;  // remember signal occurred
        clk.signal();  // signal lost if not waiting
        mlk.release();
    }
  public:
    T2( uOwnerLock & mlk,
        uCondLock & clk ) :
        mlk(mlk), clk(clk) {}
};
```

```
int main() {
    uOwnerLock mlk;
    uCondLock clk;
    T1 t1( mlk, clk );
    T2 t2( mlk, clk );
}
```

6.3.3 Barrier

- A **barrier** coordinates a group of tasks performing a concurrent operation surrounded by sequential operations.
- Hence, a barrier is for synchronization and cannot build mutual exclusion.
- Two kinds of barrier: threads equal group size (T == G) or threads greater than group size (T > G).
- Unlike previous synchronization locks, a ***barrier retains state about the events it manages***: number of tasks blocked on the barrier.
- Since manipulation of this state requires mutual exclusion, most barriers use internal locking.

- E.g., 3 tasks must execute a section of code in a particular order: S1, S2 and S3 must *all* execute before S5, S6 and S7.

```
T1::main() {        T2::main() {        T3::main() {
    . . .               . . .               . . .
    S1                  S2                  S3
    b.block();          b.block();          b.block();
    S5                  S6                  S7
    . . .               . . .               . . .
}                   }                   }
int main() {
    Barrier b( 3 );
    T1 x( b );
    T2 y( b );
    T3 z( b );
}
```

- Barrier is initialized to control 3 tasks and passed to each task by reference (not copied).
- Barrier blocks each task at call to block until all tasks have called block.
- Last task to call block does not block and releases other tasks (cooperation).
- Hence, all tasks leave together (synchronized) after arriving at the barrier.
- Note, must specify in advance total number of block operations before tasks released.
- Two common uses for barriers:

one shot   cyclic

```
Barrier start(N+1), end(N+1); // shared
Coordinator
// start N tasks so they can initialize
// general initialization
start.block(); // wait for threads to start
// do other work
end.block();  // wait for threads to end
// general close down and possibly loop
```

```
Workers

// initialize
start.block(); // wait for threads to start
// do work
end.block();  // wait for threads to end
// close down
```

- Two barriers allow Coordinator to accumulate results (subtotals) while Workers reinitialize (read next row).
- Alternative is last Worker does coordination, but prevents Workers reinitializing during coordination.
- Why not use termination synchronization and create new tasks for each computation?
  - creation and deletion of computation tasks is expensive

6.3.3.1 Fetch Increment Barrier

- spinning, T == G, flag ensures waiting threads exit barrier even if fast threads change count.

```
struct Barrier {
    size_t group = 0;
    volatile bool flag = false;
    volatile size_t count = 0;
};
void block( Barrier & b ) {
    size_t negflag = ! b.flag;
    if ( FetchInc( b.count, 1 ) < b.group - 1 ) {
        await( b.flag == negflag ); // spin
    } else {
        // SAFE ACTION BEFORE TRIGGERING BARRIER
        b.count = 0;
        b.flag = negflag;
    }
}
```

- Construct failure scenario for await(b.count == 0).

6.3.3.2 uBarrier

- μC++ barrier is a blocking, T > G, barging-prevention coroutine, where the coroutine main can be resumed by the last task arriving at the barrier.

```
#include <uBarrier.h>
_Cormonitor uBarrier {                      // think _Coroutine
  protected:
    void main() { for ( ;; ) suspend(); }   // points of synchronization
    virtual void last() { resume(); }       // called by last task to barrier
  public:
    uBarrier( unsigned int total );
    unsigned int total() const;             // # of tasks synchronizing
    unsigned int waiters() const;           // # of waiting tasks
    void reset( unsigned int total );       // reset # tasks synchronizing
    virtual void block(); // wait for Nth thread, which calls last, unblocks waiting thread
};
```

- Member last is called by the Nth (last) task to the barrier, and then all blocked tasks are released.
- uBarrier has implicit mutual exclusion ⇒ no barging ⇒ only manages synchronization
- User barrier is built by:
  - inheriting from uBarrier
  - redefining last and/or block member and possibly coroutine main
  - possibly initializing main from constructor

- E.g., previous matrix sum (see page 79) adds subtotals in order of task termination, but barrier can add subtotals in order produced.

```
_Cormonitor Accumulator : public uBarrier {
    int total_ = 0, temp;
    uBaseTask * Nth_ = nullptr;
  protected:
    void last() {  // reset and remember Nth task
        temp = total_; total_ = 0;
        Nth_ = &uThisTask();
    }
  public:
    Accumulator( int rows ) : uBarrier( rows ) {}
    void block( int subtotal ) {
        total_ += subtotal;
        uBarrier::block();
    }
    int total() { return temp; }
    uBaseTask * Nth() { return Nth_; }
};

_Task Adder {
    int * row, size;
    Accumulator & acc;
    void main() {
        int subtotal = 0;
        for ( unsigned int r = 0; r < size; r += 1 ) subtotal += row[r];
        acc.block( subtotal );  // provide subtotal; block for completion
    }
  public:
    Adder( int row[ ], int size, Accumulator & acc ) :
        size( size ), row( row ), acc( acc ) {}
};

int main() {
    enum { rows = 10, cols = 10 };
    int matrix[rows][cols];
    Accumulator acc( rows );  // barrier synchronizes each summation
    // read matrix
    {
        uArray( Adder, adders, rows );
        for ( unsigned int r = 0; r < rows; r += 1 )
            adders[r]( matrix[r], cols, acc );
    } // wait adders
    cout << acc.total() << " " << acc.Nth() << endl;
}
```

- Why not have task delete itself after unblocking from **uBarrier::block()** and make program main the coordinator?

```
void block( int subtotal ) {
    total_ += subtotal; uBarrier::block();
    delete &uThisTask();
}
// program main
acc.block( 0 );
```

- Coroutine barrier can be reused many times, e.g., read in a new matrix in Accumulator::main after each summation.
- Why can a barrier not be used within a COFOR?

6.3.4 Binary Semaphore

- **Binary semaphore** (Edsger W. Dijkstra) is blocking equivalent to yielding spin-lock.
- Provides synchronization *and* mutual exclusion.

```
Semaphore lock(0);   // 0 => closed, 1 => open, default 1
```

- More powerful than synchronization lock as it remembers state about an event.
- Names for acquire and release from Dutch terms
- acquire is P
  - passeren ⇒ to pass
  - prolagen ⇒ (proberen) to try (verlagen) to decrease

  ```
  lock.P();            // wait to enter
  ```

  P waits if the semaphore counter is zero and then decrements it.
- release is V
  - vrijgeven ⇒ to release
  - verhogen ⇒ to increase

  ```
  lock.V();            // release lock
  ```

  V increases the counter and unblocks a waiting task (if present).
- When the semaphore has only two states (open/closed), it is called a **binary semaphore**.
- synchronization

`_Task T1 {`
`    BinSem & lk;`
`    void main() {`
`        . . .`
`        S1`
`        lk.V();`
`        . . .`
`    }`
`  public:`
`    T1( BinSem & lk ) : lk(lk) {}`
`};`
	`_Task T2 {`
	`    BinSem & lk;`
	`    void main() {`
	`        . . .`
	`        lk.P();`
	`        S2`
	`        . . .`
	`    }`
	`  public:`
	`    T2( BinSem & lk ) : lk(lk) {}`
	`};`

```
int main() {
    BinSem lock( 0 ); // closed
    T1 t1( lock );
    T2 t2( lock );
}
```

- mutual exclusion

```
_Task T {
    BinSem & lk;
    void main() {
        . . .
        lk.P();
        // critical section
        lk.V();
        . . .
        lk.P();
        // critical section
        lk.V();
        . . .
    }
  public:
    T( BinSem & lk ) : lk(lk) {}
};
```

```
int main() {
    BinSem lock( 1 ); // start open
    T t0( lock ), t1( lock );
}
```

6.3.4.1 Implementation

- Implementation has:
  - blocking task-list
  - avail indicates if event has occurred (state)
  - spin lock to protect state

```
class BinSem {
    queue<Task> blocked;        // blocked tasks
    bool avail;                 // resource available ?
    SpinLock lock;              // mutex nonblocking lock
  public:
    BinSem( bool start = true ) : avail( start ) {}
    void P() {
        lock.acquire();         // prevention barging
        if ( ! avail ) {
            // add self to lock' s blocked list
            yieldNoSchedule( lock );
            // DO NOT REACQUIRE LOCK
        }
        avail = false;
        lock.release();
    }
```

```
        void V() {
            lock.acquire();
            if ( ! blocked.empty() ) {
                // remove task from blocked list and make ready
                // DO NOT RELEASE LOCK
            } else {
                avail = true;           // conditional reset
                lock.release();         // NO RACE
            }
        }
    };
```

- Same as single-acquisition mutexLock but can initialize avail.
- Higher cost for synchronization if external lock already acquired.

6.3.5 Counting Semaphore

- Augment the definition of P and V to allow a multi-valued semaphore.
- What does it mean for a lock to have more than open/closed (unlocked/locked)?
  - ⇒ critical sections allowing *N* simultaneous tasks.
- Augment V to allow increasing the counter an arbitrary amount.
- synchronization
  - Three tasks must execute so S2 and S3 only execute after S1 has completed.

```
T1::main() {        T2::main() {        T3::main() {
    . . .               . . .               S1
    lk.P();             lk.P();             lk.V(); // lk.V(2)
    S2                  S3                  lk.V();
    . . .               . . .               . . .
}                   }                   }
int main() {
    CntSem lk( 0 ); // closed
    T1 x( lk );
    T2 y( lk );
    T3 z( lk );
}
```

- mutual exclusion
  - Critical section allowing up to 3 simultaneous tasks.

```
_Task T {
    CntSem & lk;
    void main() {
        . . .
        lk.P();
        // up to 3 tasks in
        // critical section
        lk.V();
        . . .
    }
  public:
    T( CntSem & lk ) : lk(lk) {}
};
```

```
int main() {
    CntSem lk( 3 ); // allow 3
    T t0( lk ), t1( lk ), . . .;
}
```

- Must know in advance the total number of P's on the semaphore.

6.3.5.1 Implementation

- Change availability into counter, and set to some maximum on creation.
- Decrement counter on acquire and increment on release.
- Block acquiring task when counter is 0.
- Negative counter indicates number of waiting tasks.

```
class CntSem {
    queue<Task> blocked;     // blocked tasks
    int cnt;                 // resource being used ?
    SpinLock lock;           // nonblocking lock
  public:
    CntSem( int start = 1 ) : cnt( start ) {}

    void P() {
        lock.acquire();
        cnt -= 1;
        if ( cnt < 0 ) {
            // add self to lock's blocked list
            yieldNoSchedule( lock );
            // DO NOT REACQUIRE LOCK
        }
        lock.release();
    }

    void V() {
        lock.acquire();
        cnt += 1;
        if ( cnt <= 0 ) {
            // remove task from blocked list and make ready
            // DO NOT RELEASE LOCK
        } else {
            lock.release();    // NO RACE
        }
    }
};
```

- In general, binary/counting semaphores are used in two distinct ways:
  1. For synchronization, if the semaphore starts at 0 ⇒ waiting for an event to occur.
  2. For mutual exclusion, if the semaphore starts at 1(N) ⇒ controls a critical section.
- μC++ provides a counting semaphore, uSemaphore, which subsumes a binary semaphore.

```
#include <uSemaphore.h>
class uSemaphore {
  public:
    uSemaphore( unsigned int count = 1 );
    void P();
    bool TryP();
    void V( unsigned int times = 1 );
    int counter() const;
    bool empty() const;
};
```

- P decrements the semaphore counter; if the counter is greater than or equal to zero, the calling task continues, otherwise it blocks.
- TryP returns **true** if the semaphore is acquired and **false** otherwise (never blocks).
- V wakes up the task blocked for the longest time if there are tasks blocked on the semaphore and increments the semaphore counter.
- If V is passed a positive integer N, the semaphore is Ved N times.
- The member routine counter returns the value of the semaphore counter:
  - negative means abs(N) tasks are blocked waiting to acquire the semaphore, and the semaphore is locked;
  - zero means no tasks are waiting to acquire the semaphore, and the semaphore is locked;
  - positive means the semaphore is unlocked and allows N tasks to acquire the semaphore.
- The member routine empty returns **false** if there are threads blocked on the semaphore and **true** otherwise.

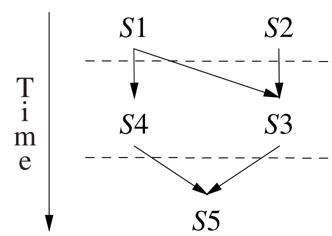
6.4 Lock Programming

6.4.1 Precedence Graph

- Binary P and V in with COBEGIN are as powerful as START and WAIT.
- E.g., execute statements so the result is the same as serial execution but concurrency is maximized.

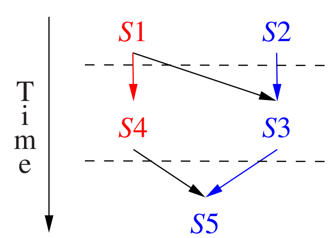
```
S1: a := 1
S2: b := 2
S3: c := a + b
S4: d := 2 * a
S5: e := c + d
```

- Analyse which data and code depend on each other.
- i.e., statement S1 and S2 are independent ⇒ can execute in either order or at the same time.
- Statement S3 is dependent on S1 and S2 because it uses both results.
- Display dependencies graphically in a **precedence graph** (different from process graph).



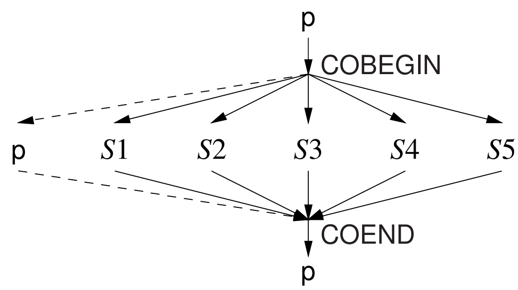

```
Semaphore L1(0), L2(0), L3(0), L4(0);
COBEGIN
    BEGIN a := 1; V(L1); END;
    BEGIN b := 2; V(L2); END;
    BEGIN P(L1); P(L2); c := a + b; V(L3); END;
    BEGIN P(L1); d := 2 * a; V(L4); END;
    BEGIN P(L3); P(L4); e := c + d; END;
COEND
```

- Does this solution work?
- Optimal solution: minimum threads, M, and traverse M paths through precedence graph.




```
Semaphore L1(0), L2(0);
COBEGIN
    BEGIN a := 1; V(L1); d := 2 * a; V(L2); END;
    BEGIN b := 2; P(L1); c := a + b; P(L2); e := c + d; END;
COEND
```

- process graph (different from precedence graph)

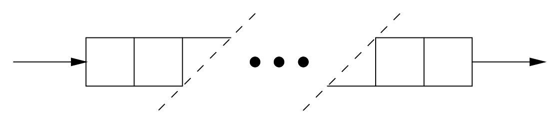


6.4.2 Buffering

- Tasks communicate unidirectionally through a queue.
- Producer adds items to the back of a queue.
- Consumer removes items from the front of a queue.

6.4.2.1 Unbounded Buffer

- Two tasks communicate through a queue of unbounded length.



- Because tasks work at different speeds, producer may get ahead of consumer.
  - Producer never has to wait as buffer has infinite length.
  - Consumer has to wait if buffer is empty ⇒ wait for producer to add.
- Queue is shared between producer/consumer, and counting semaphore controls access.

```
#define QueueSize ∞
int front = 0, back = 0;
int Elements[QueueSize];
uSemaphore full(0);
void Producer::main() {
    for (;;) {
        // produce an item
        // add to back of queue
        full.V();
    }
    // produce a stopping value
    full.V();
}
```

```
void Consumer::main() {
    for (;;) {
        full.P();
        // take an item from the front of the queue
      if ( stopping value ? ) break;
        // process or consume the item
    }
}
```

- Is there a problem adding and removing items from the shared queue?
- Is the full semaphore used for mutual exclusion or synchronization?

6.4.2.2 Bounded Buffer

- Two tasks communicate through a queue of bounded length.
- Because of bounded length:
  - Producer has to wait if buffer is full ⇒ wait for consumer to remove.
  - Consumer has to wait if buffer is empty ⇒ wait for producer to add.
- Use counting semaphores to account for the finite length of the shared queue.

```
uSemaphore full(0), empty(QueueSize);
void Producer::main() {
    for ( ;; ) {
        // produce an item
        empty.P();
        // add element to buffer
        full.V();
    }
    // produce a stopping value
    full.V();
}
void Consumer::main() {
    for ( ;; ) {
        full.P();
        // remove element from buffer
      if ( stopping value ? ) break;
        // process or consume the item
        empty.V();
    }
}
```

- Does this produce maximum concurrency?
- Can it handle multiple producers/consumers?

34	13	9	10	-3

full	empty
~~0~~	~~5~~
~~1~~	~~4~~
~~2~~	~~3~~
~~3~~	~~2~~
~~4~~	~~1~~
5	0

6.4.3 Lock Techniques

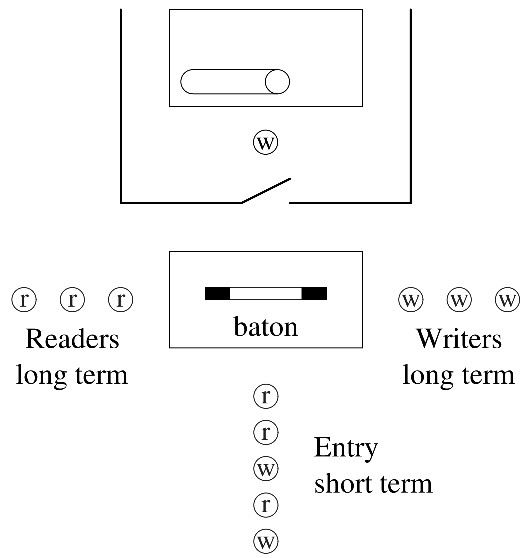
- Many possible solutions; need systematic approach.
- A **split binary semaphore** is a collection of semaphores where at most one of the collection has the value 1.
  - I.e., the sum of the semaphores is always less than or equal to one.
  - Used when different kinds of tasks have to block separately.
  - Cannot differentiate tasks blocked on the same semaphore (condition) lock. Why?
  - E.g., A and B tasks block on different semaphores so they can be unblocked based on kind, but collectively manage 2 semaphores like it was one.
- Split binary semaphores can be used to solve complicated mutual-exclusion problems by a technique called **baton passing**.
- The rules of baton passing are:
  - there is exactly one (conceptual) baton
  - nobody moves in the entry/exit code unless they have it
  - once the baton is released, cannot read/write variables in entry/exit
- E.g., baton is conceptually acquired in entry/exit protocol and passed from signaller to signalled task (see page 104).

```
class BinSem {
    queue<Task> blocked;
    bool avail;
    SpinLock lock;
  public:
    BinSem( bool start = true ) : avail( start ) {}
    void P() {
        lock.acquire(); PICKUP BATON, CAN ACCESS STATE
        if ( ! avail ) {
            // add self to lock' s blocked list
            PUT DOWN BATON, CANNOT ACCESS STATE
            yieldNoSchedule( lock );
            // UNBLOCK WITH SPIN LOCK ACQUIRED
            PASSED BATON, CAN ACCESS STATE
        }
        avail = false;
        lock.release(); PUT DOWN BATON, CANNOT ACCESS STATE
    }
    void V() {
        lock.acquire(); PICKUP BATON, CAN ACCESS STATE
        if ( ! blocked.empty() ) {
            // remove task from blocked list and make ready
            PASS BATON, CANNOT ACCESS STATE
        } else {
            avail = true;
            lock.release(); PUT DOWN BATON, CANNOT ACCESS STATE
        }
    }
};
```

- Can mutex/condition lock perform baton passing to prevent barging?
  - Not if signalled task must implicitly re-acquire the mutex lock before continuing.
  - ⇒ signaller must release the mutex lock.
  - There is now a race between signalled and calling tasks, resulting in barging.

6.4.4 Readers and Writer Problem

- Multiple tasks sharing a resource: some reading the resource and some writing the resource.
- Allow multiple concurrent reader tasks simultaneous access, but serialize access for writer tasks (a writer may read).
- Use split-binary semaphore to segregate 3 kinds of tasks: arrivers, readers, writers.
- Use baton-passing to help understand complexity.



6.4.4.1 Solution 1

```
uSemaphore entry(1), rwait(0), wwait(0); // split binary semaphores
int rdel = 0, wdel = 0, rcnt = 0, wcnt = 0; // auxiliary counters
void Reader::main() {
    entry.P();                          // pickup baton
    if ( wcnt > 0 ) {                   // occupied ?
        rdel += 1; entry.V();           // put baton down
        rwait.P(); rdel -= 1;           // passed baton
    }
    rcnt += 1;
    if ( rdel > 0 ) {                   // waiting readers ?
        rwait.V();                      // pass baton
    } else {
        entry.V();                      // put baton down
    }
    // READ
    entry.P();                          // pickup baton
    rcnt -= 1;
    if ( rcnt == 0 && wdel > 0 ) {      // waiting writers ?
        wwait.V();                      // pass baton
    } else {
        entry.V();                      // put baton down
    }
}
```

```
void Writer::main() {
    entry.P();                          // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {       // occupied ?
        wdel += 1; entry.V();           // put baton down
        wwait.P(); wdel -= 1;           // passed baton
    }
    wcnt += 1;
    entry.V();                          // put baton down
    // WRITE
    entry.P();                          // pickup baton
    wcnt -= 1;
    if ( rdel > 0 ) {                   // waiting readers ?
        rwait.V();                      // pass baton
    } else if ( wdel > 0 ) {            // waiting writers ?
        wwait.V();                      // pass baton
    } else {
        entry.V();                      // put baton down
    }
}
```

- Problem: reader only checks for writer in resource, never writers waiting to use it.
  - ⇒ readers barge ahead of writers who already waited.
  - ⇒ continuous stream of readers (actually only 2 needed) prevent waiting writers from making progress (starvation).

6.4.4.2 Solution 2

- Give writers priority and make the readers wait.
  - Works most of the time because normally 80% readers and 20% writers.
- Change entry protocol for reader to the following:

```
entry.P();                              // pickup baton
if ( wcnt > 0 || wdel > 0 ) {           // waiting writers?
    rdel += 1; entry.V();               // put baton down
    rwait.P(); rdel -= 1;               // passed baton
}
rcnt += 1;
if ( rdel > 0 ) {                       // waiting readers ?
    rwait.V();                          // pass baton
} else {
    entry.V();                          // put baton down
}
```

- Also, change writer's exit protocol to favour writers:

```
entry.P();                      // pickup baton
wcnt -= 1;
if ( wdel > 0 ) {               // check writers first
    wwait.V();                  // pass baton
} else if ( rdel > 0 ) {
    rwait.V();                  // pass baton
} else {
    entry.V();                  // put baton down
}
```

- ⇒ writers barge.
- ⇒ continuous stream of writers cause reader starvation.

6.4.4.3 Solution 3

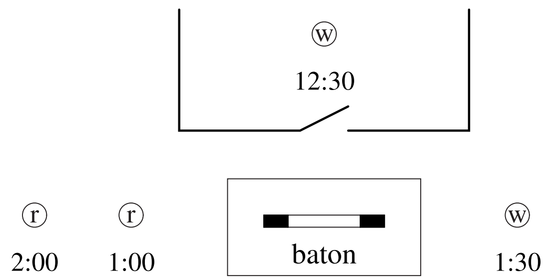
- Fairness on simultaneous arrival is solved by alternation (Dekker's solution).
- E.g., use last flag to indicate the kind of tasks last using the resource, i.e., reader or writer.
- On exit, first select from opposite kind, e.g., if last is reader, first check for waiting writer otherwise waiting reader, then update last.
- Flag is unnecessary if readers wait when there is a waiting writer, and all readers started after a writer.
- ⇒ put writer's exit-protocol back to favour readers.

```
entry.P();                      // pickup baton
wcnt -= 1;
if ( rdel > 0 ) {               // check readers first
    rwait.V();                  // pass baton
} else if ( wdel > 0 ) {
    wwait.V();                  // pass baton
} else {
    entry.V();                  // put baton down
}
```

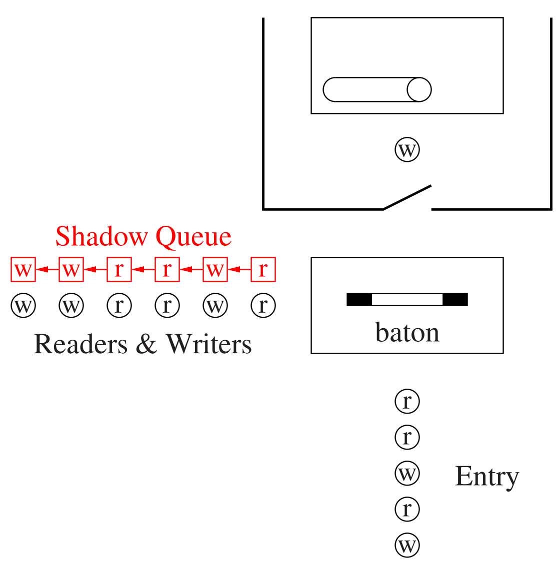
- **Arriving** readers cannot barge ahead of waiting writers and **unblocking** writers cannot barge ahead of a waiting reader
- ⇒ alternation for simultaneous waiting.

6.4.4.4 Solution 4

- Problem: temporal barging!
- Staleness/freshness for last flag and staleness with no-flag.



- Alternation for simultaneous waiting means when writer leaves resource:
  - both readers enter ⇒ 2:00 reader reads data that is **stale**; should read 1:30 write
  - writer enters and overwrites 12:30 data (never seen) ⇒ 1:00 reader reads data that is too **fresh** (i.e., missed reading 12:30 data)
- Staleness/freshness can lead to plane or stock-market crash.
- Service readers and writers in **temporal order**, i.e., first-in first-out (FIFO), but allow multiple concurrent readers.
- Have readers and writers wait on same semaphore ⇒ collapse split binary semaphore.
- ***But now lose kind of waiting task!***
- Introduce shadow queue to retain kind of waiting task on semaphore:



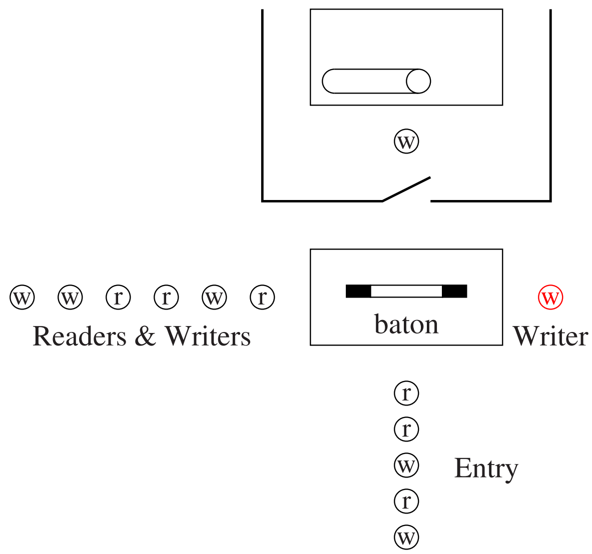
```
uSemaphore entry(1), rwwait(0);          // readers/writers, temporal order
int rwdel = 0, rcnt = 0, wcnt = 0;       // auxiliary counters
enum RW { READER, WRITER };              // kinds of tasks
queue<RW> rw_id;                         // queue of kinds
void Reader::main() {
    entry.P();                           // pickup baton
    if ( wcnt > 0 || rwdel > 0 ) {       // anybody waiting?
        rw_id.push( READER );            // store kind
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        rw_id.pop();
    }
    rcnt += 1;
    if ( rwdel > 0 && rw_id.front() == READER ) { // more readers ?
        rwwait.V();                      // pass baton
    } else
        entry.V();                       // put baton down
    // READ
    entry.P();                           // exit protocol
    rcnt -= 1;
    if ( rcnt == 0 && rwdel > 0 ) {      // last reader ?
        rwwait.V();                      // pass baton
    } else
        entry.V();                       // put baton down
}

void Writer::main() {
    entry.P();                           // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {
        rw_id.push( WRITER );            // store kind
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        rw_id.pop();
    }
    wcnt += 1;
    entry.V();                           // put baton down
    // WRITE
    entry.P();                           // pickup baton
    wcnt -= 1;
    if ( rwdel > 0 ) {                   // anyone waiting ?
        rwwait.V();                      // pass baton
    } else
        entry.V();                       // put baton down
}
```

- Why can task pop *front* node on shadow queue when unblocked?

6.4.4.5 Solution 5

- Cheat on cooperation:
  - allow 2 checks for write instead of 1
  - use reader/writer bench and writer chair.

- On exit, if chair empty, unconditionally unblock task at front of reader/writer semaphore.
- ⇒ ***reader can incorrectly unblock a writer.***
- This writer now waits second time but in chair.
- Chair is always checked first on exit (higher priority than bench).




```
uSemaphore entry(1), rwwait(0), wwait(0);
int rwdel = 0, wdel = 0, rcnt = 0, wcnt = 0; // auxiliary counters
void Reader::main() {
	entry.P();                              // pickup baton
	if ( wcnt > 0 || wdel > 0 || rwdel > 0 ) {
		rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
	}
	rcnt += 1;
	if ( rwdel > 0 ) {                      // more readers ?
		rwwait.V();                         // pass baton
	} else
		entry.V();                          // put baton down
	// READ
	entry.P();                              // pickup baton
	rcnt -= 1;
	if ( rcnt == 0 ) {                      // last reader ?
		if ( wdel != 0 ) {                  // writer waiting ?
			wwait.V();                      // pass baton
		} else if ( rwdel > 0 ) {           // anyone waiting ?
			rwwait.V();                     // pass baton
		} else
			entry.V();                      // put baton down
	} else
		entry.V();                          // put baton down
}
```

```
void Writer::main() {
    entry.P();                          // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {       // first wait ?
        rwdel += 1; entry.V(); rwwait.P(); rwdel -= 1;
        if ( rcnt > 0 ) {               // second wait ?
            wdel += 1; entry.V(); wwait.P(); wdel -= 1;
        }
    }
    wcnt += 1;
    entry.V();                          // put baton down
    // WRITE
    entry.P();                          // pickup baton
    wcnt -= 1;
    if ( rwdel > 0 ) {                  // anyone waiting ?
        rwwait.V();                     // pass baton
    } else
        entry.V();                      // put baton down
}
```

6.4.4.6 Solution 6

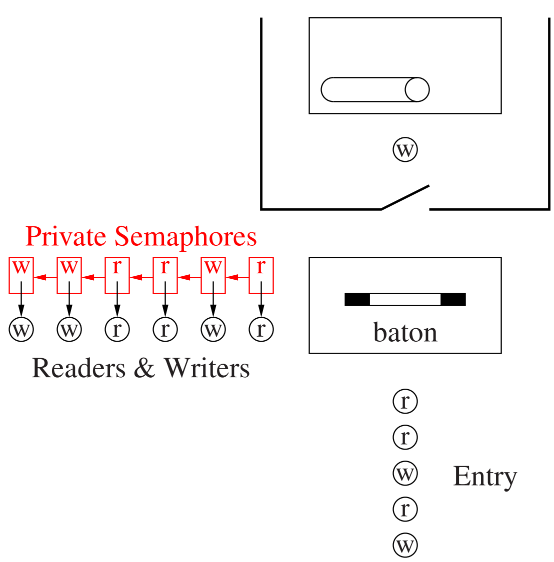
- Still temporal problem when tasks move from one blocking list to another.
- In solutions, reader/writer entry-protocols have code sequence:

```
... entry.V(); INTERRUPTED HERE Xwait.P();
```

- For writer:
  - pick up baton and see readers using resource
  - put baton down, entry.V(), but time-sliced before wait, Xwait.P().
  - another writer does same thing, and this can occur to any depth.
  - writers restart in any order or immediately have another time-slice
  - e.g., 2:00 writer goes ahead of 1:00 writer ⇒ freshness problem.
- For reader:
  - pick up baton and see writer using resource
  - put baton down, entry.V(), but time-sliced before wait, Xwait.P().
  - writers that arrived ahead of reader do same thing
  - reader restarts before any writers
  - e.g., 2:00 reader goes ahead of 1:00 writer ⇒ staleness problem.
- Need atomic block and release ⇒ magic like turning off time-slicing.

```
Xwait.P( entry );       // uC++ semaphore
```

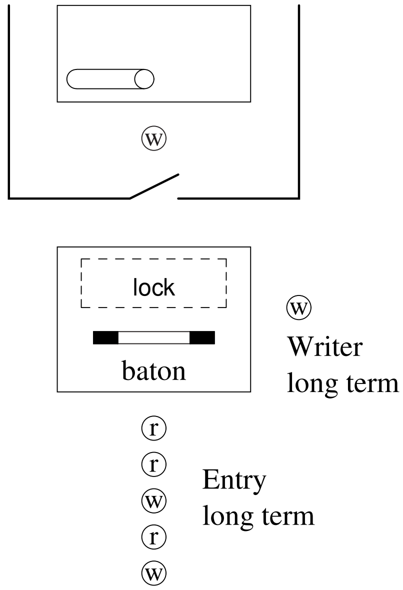
- Alternative: ticket
  - readers/writers take ticket (see Section 5.18.9, p. 93) before putting baton down
  - to pass baton, serving counter is incremented and then **WAKE ALL BLOCKED TASKS**
  - each task checks ticket with serving value, and one proceeds while others reblock
  - starvation not an issue as waiting queue is bounded length, but inefficient
- Alternative: private semaphore
  - list of **private semaphore**s, one for each waiting task, versus multiple waiting tasks on a semaphore.
  - add list node before releasing entry lock, which establishes position, then block on private semaphore.
  - to pass baton, private semaphore at head of the queue is Ved, if present.
  - if task blocked on private semaphore, it is unblocked
  - if task not blocked due to time-slice, V is remembered, and task does not block on P.



```
uSemaphore entry(1);
int rwdel = 0, rcnt = 0, wcnt = 0;
struct RWnode {
    RW rw;                          // kinds of task
    uSemaphore sem;                 // private semaphore
    RWnode( RW rw ) : rw(rw), sem(0) {}
};
queue<RWnode *> rw_id;
void Reader::main() {
    entry.P();                      // pickup baton
    if ( wcnt > 0 || ! rw_id.empty() ) { // anybody waiting?
        RWnode r( READER );
        rw_id.push( &r );           // store kind
        rwdel += 1; entry.V(); r.sem.P(); rwdel -= 1;
        rw_id.pop();
    }
    rcnt += 1;
    if ( rwdel > 0 && rw_id.front()->rw == READER ) { // more readers ?
        rw_id.front()->sem.V(); // pass baton
    } else
        entry.V();                  // put baton down
    // READ
    entry.P();                      // pickup baton
    rcnt -= 1;
    if ( rcnt == 0 && rwdel > 0 ) {    // last reader ?
        rw_id.front()->sem.V(); // pass baton
    } else
        entry.V();                  // put baton down
}

void Writer::main() {
    entry.P();                      // pickup baton
    if ( rcnt > 0 || wcnt > 0 ) {   // resource in use ?
        RWnode w( WRITER );
        rw_id.push( &w );           // remember kind of task
        rwdel += 1; entry.V(); w.sem.P(); rwdel -= 1;
        rw_id.pop();
    }
    wcnt += 1;
    entry.V();
    // WRITE
    entry.P();                      // pickup baton
    wcnt -= 1;
    if ( rwdel > 0 ) {              // anyone waiting ?
        rw_id.front()->sem.V();     // pass baton
    } else
        entry.V();                  // put baton down
}
```

6.4.4.7 Solution 7

- Ad hoc solution with questionable split-binary semaphores and baton-passing.



- Tasks wait in temporal order on entry semaphore.
- Only one writer ever waits on the writer chair until readers leave resource.
- ***Waiting writer blocks holding baton to force other arriving tasks to wait on entry.***
- Semaphore lock is used only for mutual exclusion.
- Sometimes acquire two locks to prevent tasks entering and leaving.
- Release in opposite order.

```
uSemaphore entry(1);                    // two locks open
uSemaphore lock(1), wwait(0);
int rcnt = 0, wdel = 0;

void Reader::main() {
    entry.P();                          // entry protocol
    lock.P();
    rcnt += 1;
    lock.V();
    entry.V();                          // put baton down
    // READ
    lock.P();                           // exit protocol
    rcnt -= 1;                          // critical section
    if ( rcnt == 0 && wdel == 1 ) {     // last reader & writer waiting ?
        lock.V();
        wwait.V();                      // pass baton
    } else
        lock.V();
}
```

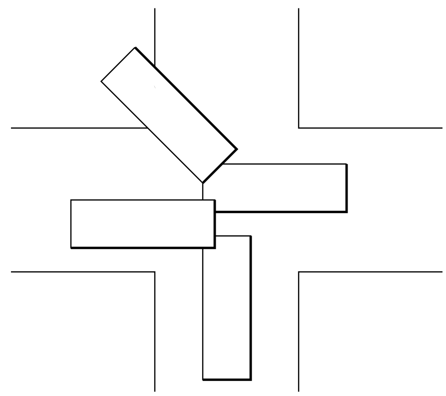
```
void Writer::main() {
    entry.P();                  // entry protocol
    lock.P();
    if ( rcnt > 0 ) {           // readers waiting ?
        wdel += 1;
        lock.V();
        wwait.P();              // wait for readers
        wdel -= 1;              // unblock with baton
    } else
        lock.V();
    // WRITE
    entry.V();                  // exit protocol
}
```

- Is temporal order preserved?
- While solution is smaller, harder to reason about correctness.
- Does not generalize for other kinds of complex synchronization and mutual exclusion.

7 Concurrent Errors

7.1 Race Condition

- A **race condition** occurs when there is missing:
  - synchronization
  - mutual exclusion

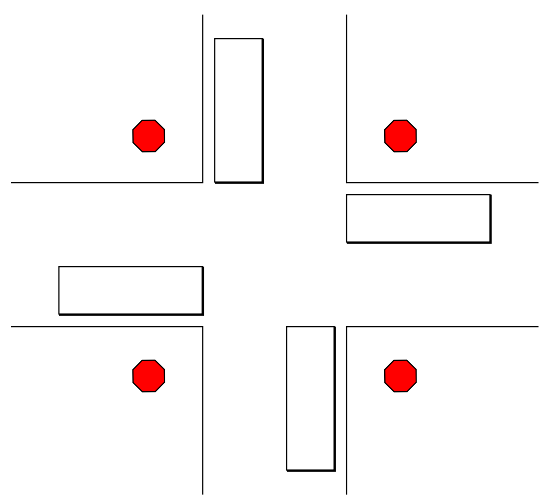


- Two or more tasks race along assuming synchronization or mutual exclusion has occurred.
- Can be very difficult to locate (thought experiments).
  - Aug. 14, 2003 Northeastern blackout : worst power outage in North American history.
  - Race condition buried in four million lines of C code.
  - "in excess of three million online operational hours in which nothing had ever exercised that bug."

7.2 No Progress

7.2.1 Live-lock

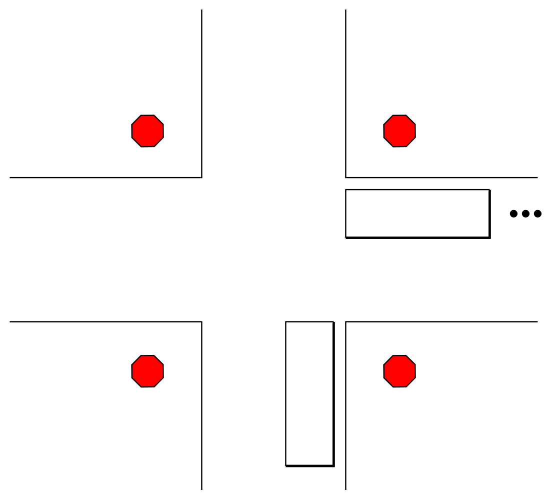
- Indefinite postponement: "You go first" problem on simultaneous arrival (consuming CPU)
- Caused by poor scheduling in entry protocol:



- There always exists some mechanism to break tie on simultaneous arrival that deals effectively with live-lock (Oracle with cardboard test).

7.2.2 Starvation

- A selection algorithm ignores one or more tasks so they are never executed, i.e., lack of long-term fairness.
- Long-term (infinite) starvation is extremely rare, but short-term starvation can occur and is a problem.



- Like live-lock, starving task might be ready at any time, switching among active, ready and possibly blocked states (consuming CPU).

7.2.3 Deadlock

- **Deadlock** is the state when one or more processes are waiting for an event that will not occur.
- Unlike live-lock/starvation, deadlocked task is blocked so not consuming CPU.

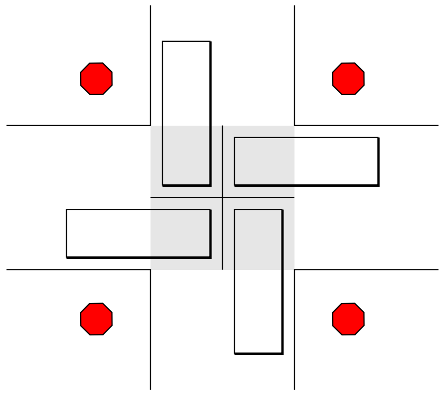
7.2.3.1 Synchronization Deadlock

- Failure in cooperation, so a blocked task is never unblocked (stuck waiting):

```
int main() {
    uSemaphore s(0);    // closed
    s.P();              // wait for lock to open
}
```

7.2.3.2 Mutual Exclusion Deadlock

- Failure to acquire a resource protected by mutual exclusion.



- Deadlock, unless one of the cars is willing to backup.
- There are 5 conditions that must occur for a set of processes to deadlock.
  1. A **concrete** shared-resource requiring mutual exclusion, i.e., exists without a task.
     - A task "wanting to drive across the intersection" is not a resource.
  2. A process holds a resource while waiting for access to a resource held by another process (hold and wait).
  3. Once a process has gained access to a resource, the runtime system cannot get it back (no preemption).
  4. There exists a circular wait of processes on resources.
  5. These conditions must occur simultaneously.
- Simple example using semaphores:

```
uSemaphore L1(1), L2(1);                          // open
     task1                  task2
L1.P()                 L2.P()                     // acquire opposite locks
     R1                     R2                    // access resource
     L2.P()                 L1.P()                // acquire opposite locks
          R1 & R2                R2 & R1          // access resources
```

7.3 Deadlock Prevention

- Eliminate one or more of the conditions required for a deadlock from an algorithm ⇒ deadlock can never occur.

7.3.1 Synchronization Prevention

- Eliminate all synchronization from a program
- ⇒ no communication
- ⇒ impossible in most cases

7.3.2 Mutual Exclusion Prevention

- Deadlock can be prevented by eliminating one of the 5 conditions:

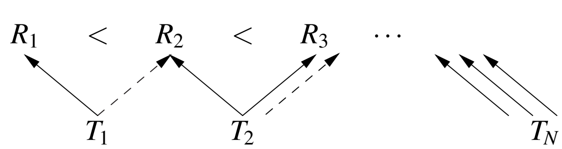
1. no mutual exclusion
   - ⇒ no shared resources
   - ⇒ impossible in most cases
2. no hold & wait: do not give any resource, unless all resources can be given

```
uSemaphore L1(1), L2(1);                        // open
     task1                   task2
L1.P() L2.P()           L1.P() L2.P()           // acquire all locks at start
     R1                      R2                 // access resource
          R1 & R2                 R2 & R1       // access resources
```

   - ⇒ poor resource utilization
   - possible starvation
3. allow preemption
   - Preemption is dynamic ⇒ cannot apply statically.
4. no circular wait: by controlling order of resource allocations

```
uSemaphore L1(1), L2(1);                        // open
     task1                   task2
L1.P()                  L1.P()                  // acquire same locks
     R1                                         // access resource
     L2.P()                  L2.P()             // acquire same locks
                                  R2            // access resource
          R1 & R2                 R2 & R1       // access resources
```

   - Use an **ordered resource** policy:



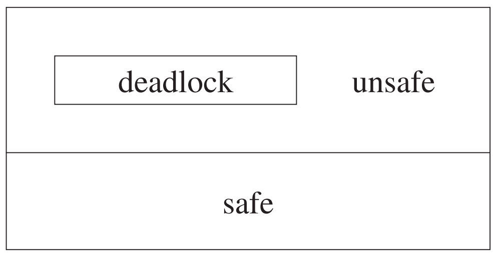
     - divide all resources into classes R_1, R_2, R_3, etc.
     - rule: can only request a resource from class R_i if holding no resources from any class R_j for $j \geq i$
     - unless each class contains only one resource, requires requesting several resources simultaneously
     - denote the highest class number for which T holds a resource by $h(T)$
     - if process T_1 is requesting a resource of class k and is blocked because that resource is held by process T_2, then $h(T_1) < k \leq h(T_2)$

- ◦ as the preceding inequality is strict, a circular wait is impossible
- ◦ in some cases there is a natural division of resources into classes that makes this policy work nicely
- ◦ in other cases, some processes are forced to acquire resources in an unnatural sequence, complicating their code and producing poor resource utilization

5. prevent simultaneous occurrence:
   - Show previous 4 rules cannot occur simultaneously.

7.4 Deadlock Avoidance

- Monitor all lock blocking and resource allocation to detect any potential formation of deadlock.



- Achieve better resource utilization, but additional overhead to avoid deadlock.

7.4.1 Banker's Algorithm

- Demonstrate a safe sequence of resource allocations that $\Rightarrow$ no deadlock.
- However, requires a process state its maximum resource needs.

	R1	R2	R3	R4	
	6	12	4	2	total resources (TR)
T1	4	10	1	1	maximum needed
T2	2	4	1	2	for execution
T3	5	9	0	1	(M)
T1	~~2~~3	5	1	0	currently
T2	1	2	1	0	allocated
T3	1	2	0	0	(C)

resource request (T1, R1) $2 \rightarrow 3$

T1	1	5	0	1	needed to
T2	1	2	0	2	execute
T3	4	7	0	1	$(N = M - C)$

- Is there a safe order of execution that avoids deadlock should each process require its maximum resource allocation?

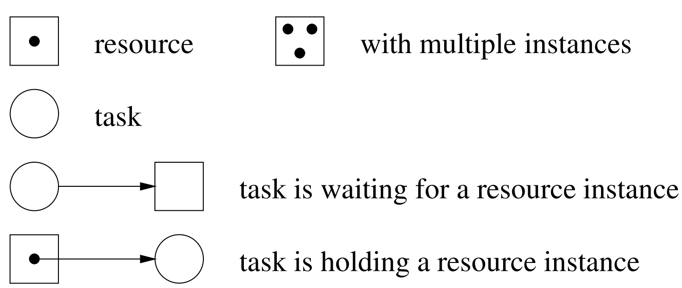
current available resources

	1	3	2	2	$(CR = TR - \sum C_{cols})$
T2	0	1	2	0	$(CR = CR - N_{T2})$
	2	5	3	2	$(CR = CR + M_{T2})$
T1	1	0	3	1	$(CR = CR - N_{T1})$
	5	10	4	2	$(CR = CR + M_{T1})$
T3	1	3	4	1	$(CR = CR - N_{T3})$
	6	12	4	2	$(CR = CR + M_{T3})$

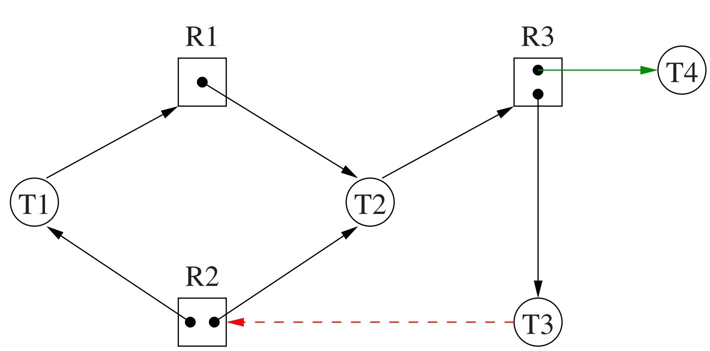
- So a safe order exists (the left column in the table above) and hence the Banker's Algorithm allows the resource request.
- If there is a choice of processes to choose for execution, it does not matter which path is taken.
- Example: If T1 or T3 could go to their maximum with the current resources, then choose either. A safe order starting with T1 exists if and only if a safe order starting with T3 exists.
- Does task scheduling need to be adjusted to the safe sequence?
- The check for a safe order can be performed for every allocation of resource to a process (optimizations are possible, i.e., same thread asks for another resource).

7.4.2 Allocation Graphs

- One method to check for potential deadlock is to graph processes and resource usage at each moment a resource is allocated.



- Multiple instances are put into a resource so that a specific resource does not have to be requested. Instead, a generic request is made.

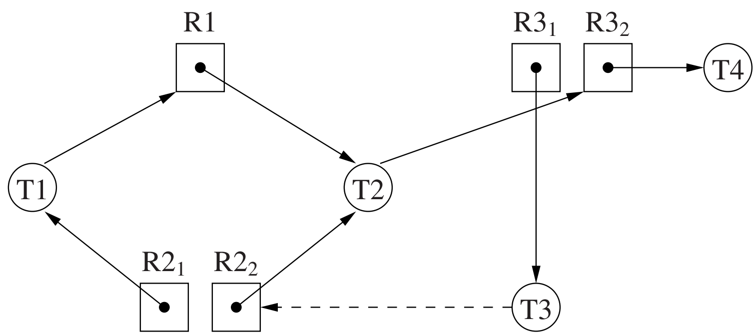


- If a graph contains no cycles, no process in the system is deadlocked.
- If any resource has several instances, a cycle $\not\Rightarrow$ deadlock.

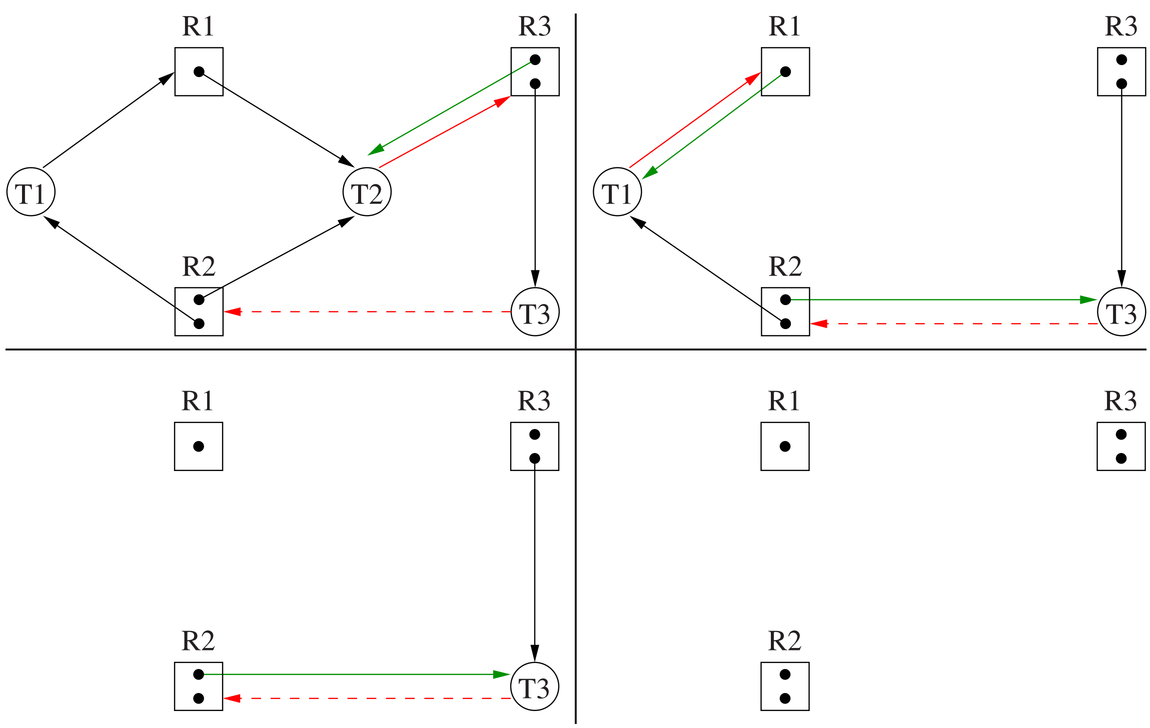
  T1 $\rightarrow$ R1 $\rightarrow$ T2 $\rightarrow$ R3 $\rightarrow$ T3 $\rightarrow$ R2 $\rightarrow$ T1 (cycle)
  T2 $\rightarrow$ R3 $\rightarrow$ T3 $\rightarrow$ R2 $\rightarrow$ T2 (cycle)

  - If T4 releases its resource, the cycle is broken.

- Create **isomorphic graph** without multiple instances (expensive and difficult):



- If each resource has one instance, a cycle $\Rightarrow$ deadlock.
- Use **graph reduction** to locate deadlocks:



- Problems:

  - When choices for tasks, selection is tricky (like isomorphic graph).
  - For large graphs, detecting cycles is expensive.
  - Many graphs to examine over time, one for each particular allocation state of the system.

7.5 Detection and Recovery

- Instead of avoiding deadlock let it happen and recover.
  - $\Rightarrow$ ability to discover deadlock
  - $\Rightarrow$ preemption
- Discovering deadlock is difficult, e.g., build and check for cycles in allocation graph.
  - not on each resource allocation, but every T seconds or every time a resource cannot be immediately allocated
  - **Try μC++ debugging macros to locate deadlock.**
- Recovery involves preemption of one or more processes in a cycle.
  - decision is not easy and must prevent starvation
  - The preemption victim must be restarted, from beginning or some previous checkpoint state, if you cannot guarantee all resources have not changed.
  - even that is not enough as the victim may have made changes before the preemption.

7.6 Which Method To Chose?

- Maybe "none of the above": just ignore the problem
  - if some process is blocked for rather a long time, assume it is deadlocked and abort it
  - do this automatically in transaction-processing systems, manually elsewhere
- Of the techniques studied, only the ordered resource policy turns out to have much practical value.

8 Indirect Communication

- P and V are low level primitives for protecting critical sections and establishing synchronization between tasks.
- Shared variables provide the actual information that is communicated.
- Both of these can be complicated to use and may be incorrectly placed.
- Split-binary semaphores and baton passing are complex.
- Need higher level facilities that perform some of these details automatically.
- Get help from programming-language/compiler.

8.1 Critical Regions

- Declare which variables are to be shared, as in:

```
VAR v : SHARED INTEGER        MutexLock v_lock;
```

- Access to shared variables is restricted to within a REGION statement, and within the region, mutual exclusion is guaranteed.

```
REGION v DO                   v_lock.acquire()
    // critical section       . . .  // x = v; (read)   v = y (write)
END REGION                    v_lock.release()
```

- Simultaneous reads are impossible!
- Modify to allow reading of shared variables outside the critical region and modifications in the region.
- Problem: reading partially updated information while a task is updating the shared variable in the region.
- Nesting can result in deadlock.

```
VAR x, y : SHARED INTEGER

task1                   task2
REGION x DO             REGION y DO
    . . .                   . . .
    REGION y DO             REGION x DO
        . . .                   . . .
    END REGION              END REGION
    . . .                   . . .
END REGION              END REGION
```

8.2 Conditional Critical Regions

- Introduce a condition that must be true as well as having mutual exclusion.

```
REGION v DO
    AWAIT conditional-expression
    . . .
END REGION
```

- E.g., The consumer from the producer-consumer problem.

```
VAR Q : SHARED QUEUE<INT,10>

REGION Q DO
    AWAIT NOT EMPTY( Q ) buffer not empty
    take an item from the front of the queue
END REGION
```

- If the condition is false, the region lock is released and entry is started again (busy waiting).
- To prevent busy waiting, block on queue for shared variable, and on region exit, search for true conditional-expression and unblock.

8.3 Monitor

- A **monitor** is an abstract data type that combines shared data with serialization of its modification.

```
_Monitor name {
    shared data
    members that see and modify the data
};
```

- A **mutex member** (short for mutual-exclusion member) is one that does NOT begin execution if there is another active mutex member.
  - ⇒ a call to a mutex member may become blocked waiting entry, and queues of waiting tasks may form.
  - Public member routines of a monitor are implicitly mutex and other kinds of members can be made explicitly mutex with qualifier (**_Mutex**).
- Basically each monitor has a lock which is Ped on entry to a monitor member and Ved on exit.

```
class Mon {
    MutexLock mlock;
    int v;
  public:
    int x(...) {                // mutex member
        mlock.acquire();
        ...         // int temp = v;
        mlock.release();
        return v;   // return temp;
    }
};
```

- Recursive entry is allowed (owner mutex lock), i.e., one mutex member can call another or itself.
- Unhandled exceptions raised within a monitor should always release the implicit monitor locks so the monitor can continue to function.
- Destructor must be mutex, so ending a block with a monitor or deleting a dynamically allocated monitor, blocks if thread in monitor.
- Atomic counter using a monitor:

```
_Monitor AtomicCounter {
    int counter;
  public:
    AtomicCounter( int init = 0 ) : counter( init ) {}
    int inc() { counter += 1; return counter; }  // mutex members
    int dec() { counter -= 1; return counter; }
};

AtomicCounter a, b, c;
... a.inc(); ...        // accessed by multiple threads
... b.dec(); ...
... c.inc(); ...
```

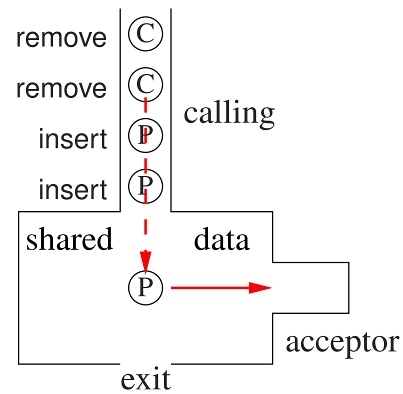
8.4 Scheduling (Synchronization)

- A monitor may want to schedule tasks in an order different from the order in which they arrive (bounded buffer, readers/write with staleness/freshness).
- There are two techniques: external and internal scheduling.
  - *external* is scheduling tasks outside the monitor and is accomplished with the accept statement.
  - *internal* is scheduling tasks inside the monitor and is accomplished using condition variables with signal & wait.

8.4.1 External Scheduling

- The accept statement controls which mutex members can accept calls.
- By preventing certain members from accepting calls at different times, it is possible to control scheduling of tasks.
- Each **_Accept** defines what cooperation must occur for the accepting task to proceed.
- E.g. Bounded Buffer

```
_Monitor BoundedBuffer {
    int front = 0, back = 0, count = 0;
    int elements[20];
  public:
    _Nomutex int query() const { return count; }
    [_Mutex] void insert( int elem );
    [_Mutex] int remove();
};
void BoundedBuffer::insert( int elem ) {
    if ( count == 20 ) _Accept( remove );
    elements[back] = elem;
    back = ( back + 1 ) % 20;
    count += 1;
}
int BoundedBuffer::remove() {
    if ( count == 0 ) _Accept( insert );
    int elem = elements[front];
    front = ( front + 1 ) % 20;
    count -= 1;
    return elem;
}
```



- Queues of tasks form outside the monitor, waiting to be accepted into either insert or remove.
- An acceptor blocks all calls except a call to the specified mutex member(s) occurs.
- Accepted call is executed like a conventional member call.
- When the accepted task exits the mutex member (or waits), the acceptor continues.
- If the accepted task does an accept, it blocks, forming a stack of blocked acceptors.
- Alternative calls that satisfy accepter's requirement are possible:

```
_Accept( insert || remove ); // one of insert or remove
```

- External scheduling is simple because unblocking (signalling) is implicit.

8.4.2 Internal Scheduling

- Scheduling among tasks inside the monitor.
- A **condition** is an external synchronization-lock (see Section 6.3.2, p. 107), i.e., queue of waiting tasks:

```
uCondition x, y, z[5];
```

- empty returns **false** if there are tasks blocked on the queue and **true** otherwise.
- front returns an integer value stored with the waiting task at the front of the condition queue.

- A task waits (blocks) by placing itself on a condition:

```
x.wait();        // wait( mutex, condition )
```

Atomically places the executing task at the back of the condition queue, and allows another task into the monitor by releasing the monitor lock.

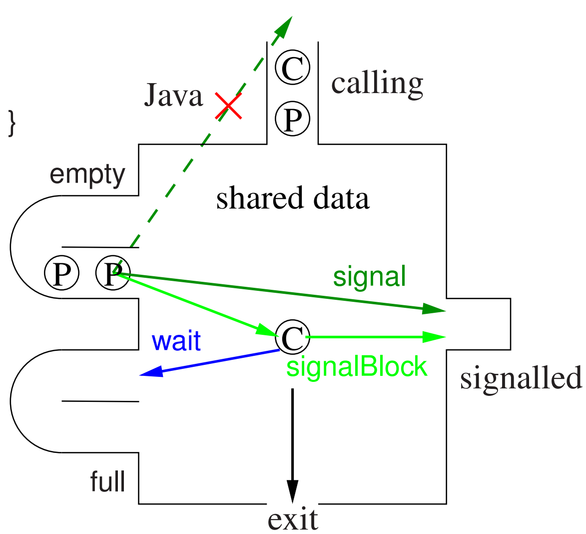
- A task on a condition queue is made ready by signalling the condition:

```
x.signal();
```

Removes and makes ready blocked task at front of the condition queue.

- **Signaller does not block, so the signalled task must continue waiting until the signaller exits or waits.**
- Like a SyncLock, a signal on an empty condition is lost!
- E.g. Bounded Buffer (like binary semaphore solution):

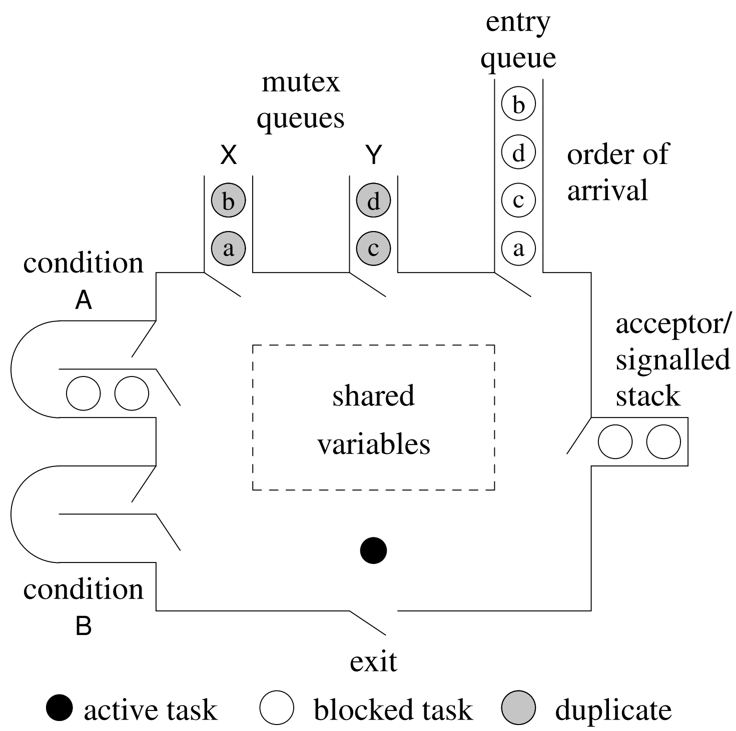
```
_Monitor BoundedBuffer {
    uCondition full, empty;
    int front = 0, back = 0, count = 0;
    int elements[20];
  public:
    _Nomutex int query() const { return count; }
    void insert( int elem ) {
        if ( count == 20 ) empty.wait();
        elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
        full.signal();
    }
    int remove() {
        if ( count == 0 ) full.wait();
        int elem = elements[front];
        front = ( front + 1 ) % 20;
        count -= 1;
        empty.signal();
        return elem;
    }
};
```



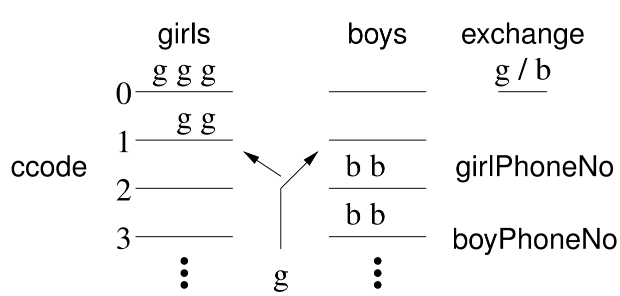
- **wait()** blocks the current thread, and restarts a signalled task or implicitly releases the monitor lock.

- **signal()** unblocks the thread on the front of the condition queue *after* the signaller thread blocks or exits.
- **signalBlock()** unblocks the thread on the front of the condition queue and blocks the signaller thread.
- General Model

```
_Monitor Mon {
    uCondition A, B;
    . . .
  public:
    int X(. . .) {. . .}
    void Y(. . .) {. . .}
};
```



- **entry queue** is FIFO list of calling tasks to the monitor.
- When to use external or internal scheduling?
- External is easier to specify and explain over internal with condition variables.
- However, external scheduling cannot be used if:
  - scheduling depends on member parameter value(s), e.g., compatibility code for dating
  - scheduling must block in the monitor but cannot guarantee the next call fulfills cooperation
- Dating service



```
_Monitor DatingService {
    enum { CCodes = 20 };   // compatibility codes
    uCondition girls[CCodes], boys[CCodes], exchange;
    int girlPhoneNo, boyPhoneNo;
  public:
    int girl( int phoneNo, int ccode ) {
        if ( boys[ccode].empty() ) {        // no compatible boy ?
            girls[ccode].wait();            // wait for boy
            girlPhoneNo = phoneNo;          // make phone number available
            exchange.signal();              // wake boy from chair
        } else {
            girlPhoneNo = phoneNo;          // make phone number available
            // signalBlock() & remove exchange
            boys[ccode].signal();           // wake boy
            exchange.wait();                // sit in chair
        }
        return boyPhoneNo;
    }
    int boy( int phoneNo, int ccode ) {
        // same as above, with boy/girl interchanged
    }
};
```

- Also, possible to use signal with empty bench (ccode) as chair.

8.5 Readers/Writer

- Solution 3 (Section 6.4.4.3, p. 128), no bargers, 5 rules, not temporal

```
_Monitor ReadersWriter {
    int rcnt = 0, wcnt = 0;
    uCondition readers, writers;
  public:
    void startRead() {
        if ( wcnt != 0 || ! writers.empty() ) readers.wait();
        rcnt += 1;
        readers.signal();
    }
    void endRead() {
        rcnt -= 1;
        if ( rcnt == 0 ) writers.signal();
    }
```

```
        void startWrite() {
            if ( wcnt !=0 || rcnt != 0 ) writers.wait();
            wcnt = 1;
        }
        void endWrite() {
            wcnt = 0;
            if ( ! readers.empty() ) readers.signal();
            else writers.signal();
        }
    };
```

- Problem: has the same protocol as P and V.

```
    ReadersWriter rw;
        readers                 writers
    rw.startRead()          rw.startWrite()     // 2-step protocol
    // read                 // write
    rw.endRead()            rw.endWrite()
```

- Simplify protocol:

```
    ReadersWriter rw;
        readers                 writers
    rw.read(...)            rw.write(...)       // 1-step protocol
```

  - Implies only one read/write action, or pass pointer to read/write action.

- Alternative interface:

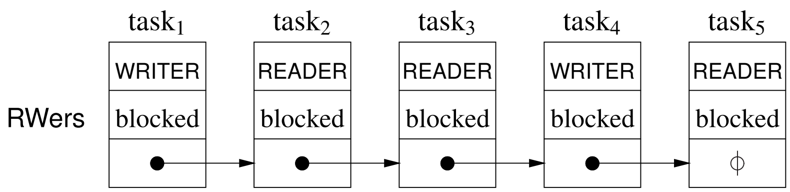
```
    _Monitor ReadersWriter {
        _Mutex void startRead() { ... }
        _Mutex void endRead() { ... }
        _Mutex void startWrite() { ... }
        _Mutex void endWrite() { ... }
      public:
        _Nomutex void read(...) { // no const or mutable
            startRead();        // acquire mutual exclusion
            // read, no mutual exclusion
            endRead();          // release mutual exclusion
        }
        _Nomutex void write(...) { // no const or mutable
            startWrite()        // acquire mutual exclusion
            // write
            endWrite()          // release mutual exclusion
        }
    };
```

- Alternative interface, and remove wcnt (barging prevention):

```
_Monitor ReadersWriter {
    _Mutex void startRead() {
        if ( ! writers.empty() ) readers.wait();
        rcnt += 1;
        readers.signal();
    }
    _Mutex void endRead() { . . . }

  public:
    _Nomutex void read(. . .) { // no const or mutable
        startRead();        // acquire mutual exclusion
        // read, no mutual exclusion
        endRead();          // release mutual exclusion
    }
    void write(. . .) {     // acquire mutual exclusion
        if ( rcnt != 0 ) writers.wait(); // release/reacquire
        // write, mutual exclusion
        if ( ! readers.empty() ) readers.signal();
        else writers.signal();
    }
};
```

- Solution 4 (Section 6.4.4.4, p. 128), condition shadow queue with type uintptr_t data.

```
_Monitor ReadersWriter {
    int rcnt = 0, wcnt = 0;
    uCondition RWers;
    enum RW { READER, WRITER };
  public:
    void startRead() {
        if ( wcnt !=0 || ! RWers.empty() ) RWers.wait( READER );
        rcnt += 1;
        if ( ! RWers.empty() && RWers.front() == READER ) RWers.signal();
    }
    void endRead() {
        rcnt -= 1;
        if ( rcnt == 0 ) RWers.signal();
    }

    void startWrite() {
        if ( wcnt != 0 || rcnt != 0 ) RWers.wait( WRITER );
        wcnt = 1;
    }
    void endWrite() {
        wcnt = 0;
        RWers.signal();
    }
};
```



- Use shadow queue to solve dating service, i.e., shadow with phone number.
- μC++ uCondLock and uSemaphore also support shadow queues with type uintptr_t data.
- Solution 8, external scheduling

```
_Monitor ReadersWriter {
    int rcnt = 0, wcnt = 0;
  public:
    void endRead() {
        rcnt -= 1;
    }
    void endWrite() {
        wcnt = 0;
    }
    void startRead() {
        if ( wcnt > 0 ) _Accept( endWrite );
        rcnt += 1;
    }
    void startWrite() {
        if ( wcnt > 0 ) _Accept( endWrite );
        else while ( rcnt > 0 ) _Accept( endRead );
        wcnt = 1;
    }
};
```

- Why has the order of the member routines changed?

8.6 Exceptions

- An exception raised in a monitor member propagates to the caller's thread.

```
_Monitor M {
  public:
    void mem1() {
        ... if ( ... ) _Throw E(); ... // E goes to caller
    } // uRendezvousFailure goes to "this"
    void mem2() {
        try {
            ... if ( ... ) _Accept( mem1 ); ...
        } catch( uMutexFailure::RendezvousFailure & ) { // implicitly enabled
            // deal with rendezvous failure
        } // try
    }
};
```

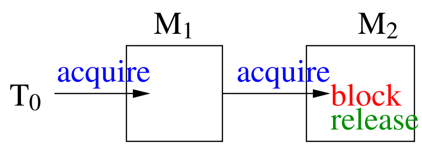
- Caller in M::mem1 gets exception E propagated on its stack.
- On exiting M::mem1, caller implicitly raises non-local RendezvousFailure exception at monitor acceptor's thread to identify failed cooperation.
- RendezvousFailure always enabled ⇒ **_Enable** block unnecessary.
- For multiple **_Accept** clauses

```
_Accept( mem2 || mem3 || ... );
```

  flag variable required to know which member failed.

8.7 Nested Monitor Calls

- **Nested monitor problem**: acquire monitor (lock) M_1, call to monitor M_2, and wait on condition in M_2.



- Monitor M_2's mutex lock is released by wait, but monitor M_1's monitor lock is NOT released ⇒ potential deadlock.
- Releasing all locks can inadvertently release a lock, e.g., incorrectly release M_0 before M_1.
- Same problem occurs with locks.
- Called **lock composition** problem.
- Nested monitor used as guardian lock for readers/writer problem (like external scheduling RW page 154).

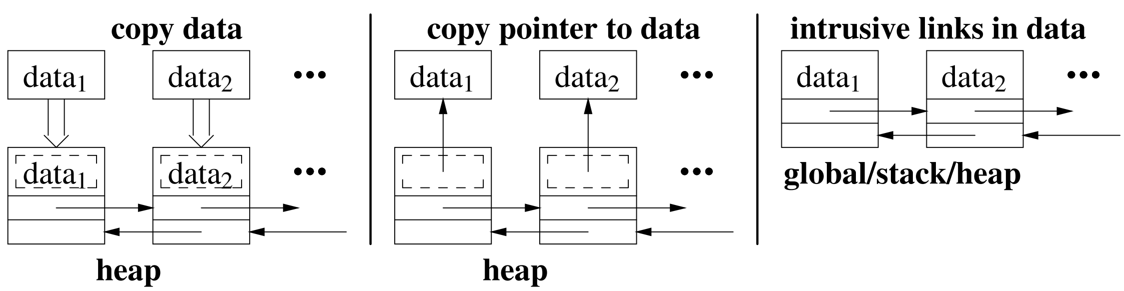
```
_Monitor RW {
    _Monitor RWN {
        uCondition bench;
        int rcnt = 0;
      public:
        void startRead() { rcnt += 1; }
        void endRead() {
            rcnt -= 1;
            if ( rcnt == 0 ) bench.signal();
        }
        void startEndWrite() {
            if ( rcnt > 0 ) bench.wait();        // blocking holding rw
            // sequential write
        }
    } rwn;
```

```
        _Mutex void mutexRead() { rwn.startRead(); }
      public:
        void write() { rwn.startEndWrite(); }
        _Nomutex void read() {
            mutexRead();
            // concurrent reads
            rwn.endRead();                      // let readers out
        }
    };
```

- If the writer waits in rwn, it prevent both readers and writers acquiring rw, which prevents starvation and forces FIFO ordering.

8.8 Intrusive Lists

- Non-contiguous variable-length data-structures, e.g., list, dictionary, normally require dynamic allocation as the structure increases/deceases when adding/deleting nodes.
- Three kinds of collections: copy data, copy pointer, and intrusive pointers:



copy creates a collection node with link fields, ⇒ dynamic allocation for links and possibly data, copies data and/or data-pointer into node, and links node into collection.

intrusive assumes a node with data and link fields, ⇒ no dynamic allocation for collection links or copying.

- Programmer manages node lifetime for copy pointer and intrusive.
- μC++ provides **intrusive data-structures** allowing global/stack/heap nodes and no copying.

```
struct Node : public uColable {
    int i;
    Node( int i ) : i{ i } {}
};
int main() {
    Node n1{ 1 }, n2{ 2 }, n3{ 3 };                    // stack nodes
    uStack<Node> s;
    s.push( &n1 ); s.push( &n2 ); s.push( &n3 );       // no dynamic allocation
    Node * sp;
    for ( uStackIter<Node> si(s); si >> sp; ) cout << sp->i << " ";
    cout << endl;
}
```

- *μ*C++ implementation uses private intrusive links for *non-copyable* objects like a coroutine or task, e.g., tasks on ready queue.
- Intrusive links have two formats: one link field (uColable) for a collection, and two link fields (uSeqable) for a sequence.


```
class stacknode : public uColable { ... }
class queuenode : public uColable { ... }
class seqnode : public uSeqable { ... }
```

- Template classes uStack/uQueue (singlely linked) are collections and uSequence (doublely linked) is a sequence.
- uSeqable node appears in sequence/collection; uColable node appears only in a collection.
- Each kind of intrusive list has associated iterators: uStackIter, uQueueIter, uSeqIter.
- See *μ*C++ reference manual Appendix C for details and examples.
- Concurrency pattern shows how threads use intrusive lists to prevent dynamic allocation.

```
if ( ... ) {
    Node n{ ... }          // allocate on thread stack
    queue.add( n );
    // block
    queue.drop();          // node n must be at head/tail of list
} // automatically free n
```

- Lifetime of node is duration of blocked thread (see above pattern in shadow queue page 130 and private semaphore page 134).

8.9 Counting Semaphore, V, P vs. Condition, Signal, Wait

- There are several important differences between these mechanisms:
  - P only blocks if semaphore = 0, wait always blocks
  - V before P affects the P, while signal before wait is lost (no state)
  - multiple Vs may start multiple tasks simultaneously, while multiple signals only start one task at a time because each task must exit serially through the monitor

- Possible to simulate P and V using a monitor:

```
_Monitor semaphore {
    int sem;
    uCondition semcond;
  public:
    semaphore( int cnt = 1 ) : sem( cnt ) {}
    void P() {
        if ( sem == 0 ) semcond.wait();
        sem -= 1;
    }
    void V() {
        sem += 1;
        semcond.signal();
    }
};
```

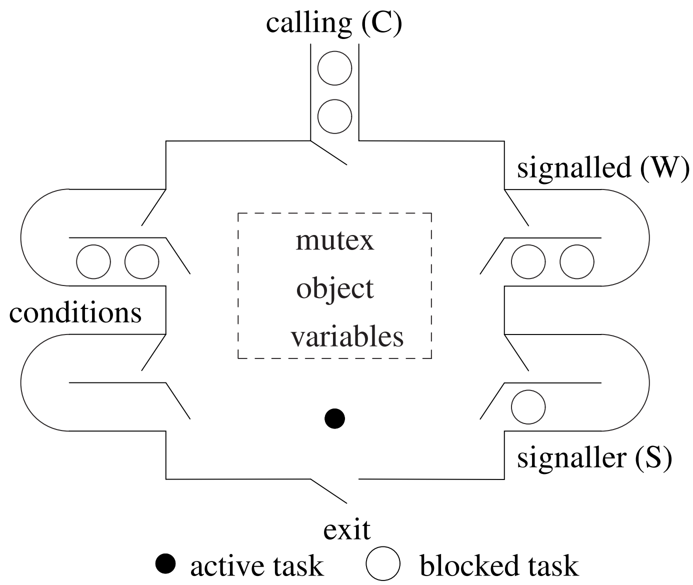
- Can this simulation be reduced?

8.10 Monitor Types

- **explicit scheduling** occurs when:
  - An accept statement blocks the active task on the acceptor stack and makes a task ready from the specified mutex member queue.
  - A signal moves a task from the specified condition to the signalled stack.
- **implicit scheduling** occurs when a task waits in or exits from a mutex member, and a new task is selected first from the A/S stack, then the entry queue.
-

explicit scheduling	internal scheduling (signal)
	external scheduling (accept)
implicit scheduling	monitor selects (wait/exit)

- Monitors are classified by the implicit scheduling (who gets control) of the monitor when a task waits or signals or exits.
- Implicit scheduling can select from the calling (C), signalled (W), and signaller (S) queues.



- Assigning different relative priorities to these queues creates different monitors (e.g., C < W < S).

	relative priority	
1	**C** < W < S	**Useful, has Prevention**
2	**C** < S < W	no barging
3	**C** = W < S	**Usable, needs Avoidance**
4	**C** = S < W	barging, starvation without avoidance
5	C = **W = S**	**Rejected**, **Confusing**
6	C < **W = S**	arbitrary selection
7	S = W < **C**	**Rejected, Unsound**
8	W < S = **C**	uncontrolled barging,
9	W < **C** < S	unpreventable starvation
10	S < W = **C**	
11	S < **C** < W	
12	W < S < **C**	
13	S < W < **C**	

- Implicit Signal
  - Monitors either have an explicit signal (statement) or an implicit signal (automatic signal).
  - The implicit signal monitor has no condition variables or explicit signal statement.
  - Instead, there is a waitUntil statement, e.g.:

    waitUntil *logical-expression*

- ◦ The implicit signal causes a task to wait until the conditional expression is true.

```
_Monitor BoundedBuffer {
        int front = 0, back = 0, count = 0;
        int elements[20];
    public:
        _Nomutex int query() const { return count; }
        void insert( int elem ) {
            waitUntil count != 20; // not in uC++
            elements[back] = elem;
            back = ( back + 1 ) % 20;
            count += 1;
        }
        int remove() {
            waitUntil count != 0; // not in uC++
            int elem = elements[front];
            front = ( front + 1 ) % 20;
            count -= 1;
            return elem;
        }
};
```

- Additional restricted monitor-type requiring the signaller exit immediately from monitor (i.e., signal ⇒ return), called **immediate-return signal**.
  - ◦ not powerful enough to handle all cases, e.g., dating service, but optimizes the most common case of signal before return.
- Remaining monitor types:

signal type	priority	no priority
Blocking	Priority Blocking (Hoare) $C < S < W$ (μC++ signalBlock)	No Priority Blocking $C = S < W$
Nonblocking	Priority Nonblocking $C < W < S$ (μC++ signal)	No Priority Nonblocking $C = W < S$ (Java/C#)
Implicit Signal	Priority Implicit Signal $C < W$	No Priority Implicit Signal $C = W$

  - ◦ no-priority blocking requires the **signaller task** to recheck the waiting condition in case of a barging task.
    ⇒ use a **while** loop around a signal
  - ◦ no-priority non-blocking requires the **signalled task** to recheck the waiting condition in case of a barging task.
    ⇒ use a **while** loop around a wait
  - ◦ implicit (automatic) signal is good for **prototyping** but have poor performance.

- ○ priority nonblocking has no barging and optimizes signal before return (supply cooperation).
- ○ priority blocking has no barging and handles internal cooperation within the monitor (wait for cooperation).

- coroutine monitor (**_Cormonitor**)
  - ○ coroutine with implicit mutual exclusion on calls to specified member routines:

```
_Mutex _Coroutine C {   // _Cormonitor
    void main() {
        . . . suspend() . . .
        . . . suspend() . . .
    }
  public:
    void m1( . . . ) { . . . resume(); . . . }   // mutual exclusion
    void m2( . . . ) { . . . resume(); . . . }   // mutual exclusion
    . . . // destructor is ALWAYS mutex
};
```

  - ○ can use resume(), suspend(), condition variables (wait(), signal(), signalBlock()) or **_Accept** on mutex members.
  - ○ coroutine can now be used by multiple threads, e.g., coroutine print-formatter accessed by multiple threads.

8.11 Java Monitor

- Java has **synchronized** class members (i.e., _Mutex members but **incorrectly named**), and a **synchronized** statement.
- All classes have **one** implicit condition variable and these routines to manipulate it:

```
public wait();
public notify();
public notifyAll()
```

  - ○ Java concurrency library has multiple conditions but incompatible with language condition (see Section 11.5.1, p. 216).
- Internal scheduling is no-priority nonblocking ⇒ **barging**
  - ○ wait statements must be in while loops to recheck conditions.
- Bounded buffer:

```
class Buffer {
    // buffer declarations
    private int count = 0;
    public synchronized void insert( int elem ) {
        while ( count == Size ) wait(); // busy-waiting
        // add to buffer
        count += 1;
        if ( count == 1 ) notifyAll();
    }
    public synchronized int remove() {
        while ( count == 0 ) wait();    // busy-waiting
        // remove from buffer
        count -= 1;
        if ( count == Size - 1 ) notifyAll();
        return elem;
    }
}
```

- Only one condition queue, producers/consumers wait together ⇒ unblock all tasks.
- Only one condition queue ⇒ certain solutions are difficult or impossible.
- Erroneous Java implementation of barrier:

```
class Barrier {                          // monitor
    private int N, count = 0;
    public Barrier( int N ) { this.N = N; }
    public synchronized void block() {
        count += 1;                      // count each arriving task
        if ( count < N )
            try { wait(); } catch( InterruptedException e ) {}
        else                             // barrier full
            notifyAll();                 // wake all barrier tasks
        count -= 1;                      // uncount each leaving task
    }
}
```

  - Nth task does notifyAll, leaves monitor and performs its ith step, and then races back (barging) into the barrier before any notified task restarts.
  - It sees count still at N and incorrectly starts its ith+1 step before the current tasks have completed their ith step.

- Fix by modifying code for Nth task to set count to 0 (barging avoidance) and removing count -= 1.

```
else {                       // barrier full
    count = 0;               // reset count
    notifyAll();             // wake all barrier tasks
}
```

- Technically, still wrong because of **spurious wakeup** ⇒ requires loop around wait.

```
if ( count < N )
    while ( ??? )  // cannot be count < N as count is always < N
        try { wait(); } catch( InterruptedException e ) {}
```

- Requires more complex implementation.

```
class Barrier {                          // monitor
    private int N, count = 0, generation = 0;
    public Barrier( int N ) { this.N = N; }
    public synchronized void block() {
        int mygen = generation;
        count += 1;                      // count each arriving task
        if ( count < N )                 // barrier not full ? => wait
            while ( mygen == generation )
                try { wait(); } catch( InterruptedException e ) {}
        else {                           // barrier full
            count = 0;                   // reset count
            generation += 1;             // next group
            notifyAll();                 // wake all barrier tasks
        }
    }
}
```

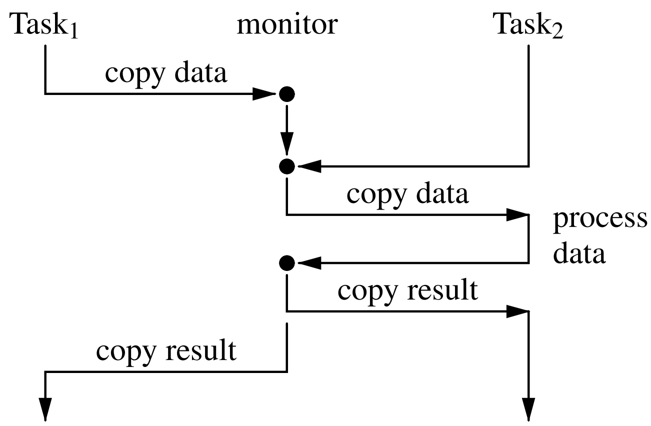
- Misconception of building condition variables in Java with nested monitors:

```
class Condition {                        // try to build condition variable
    public synchronized void Wait() {
         try { wait(); } catch( InterruptedException ex ) {};
    }
    public synchronized void Notify() { notify(); }
}
class BoundedBuffer {
    // buffer declarations
    private Condition full = new Condition(), empty = new Condition();
    public synchronized void insert( int elem ) {
        while ( count == NoOfElems ) empty.Wait(); // block producer
        // add to buffer
        count += 1;
        full.Notify();                   // unblock consumer
    }
    public synchronized int remove() {
        while ( count == 0 ) full.Wait(); // block consumer
        // remove from buffer
        count -= 1;
        empty.Notify();                  // unblock producer
        return elem;
    }
}
```

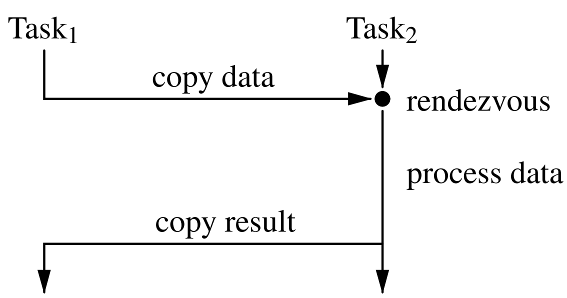
- Deadlocks at empty.Wait()/full.Wait() as buffer monitor-lock is not released.

9 Direct Communication

- Monitors work well for passive objects that require mutual exclusion because of sharing.
- However, communication among tasks with a monitor is indirect.
- Problem: point-to-point with reply indirect communication:



- Point-to-point with reply direct communication:



- Tasks can communicate directly by calling each others member routines.

9.1 Task

- A task is like a coroutine because it has a distinguished member, (task main), which has its own execution state.
- A task is unique because it has a thread of control, which begins execution in the task `main` when the task is created.
- A task is like a monitor because it provides mutual exclusion (and synchronization) so only one thread is active in the object.
  - public members of a task are implicitly mutex and other kinds of members can be made explicitly mutex.

- external scheduling allows direct calls to mutex members (task's thread blocks while caller's executes).
- without external scheduling, tasks must *call out* to communicate ⇒ third party, or somehow emulate external scheduling with internal.

- In general, basic execution properties produce different abstractions:

object properties		member routine properties	
thread	stack	No S/ME	S/ME
No	No	**1** class	**2** monitor
No	Yes	**3** coroutine	**4** coroutine-monitor
Yes	No	**5** **reject**	**6** **reject**
Yes	Yes	**7** **reject?**	**8** task

- When thread or stack is missing it comes from calling object.
- Abstractions are not ad-hoc, rather derived from basic properties.
- Each of these abstractions has a particular set of problems it can solve, and therefore, each has a place in a programming language.

9.2 Scheduling

- A task may want to schedule access to itself by other tasks in an order different from the order in which requests arrive.
- As for monitors, there are two techniques: external and internal scheduling.

9.2.1 External Scheduling

- As for a monitor (see Section 8.4.1, p. 148), the accept statement can be used to control which mutex members of a task can accept calls.

```
_Task BoundedBuffer {
    int front = 0, back = 0, count = 0;
    int Elements[20];
  public:
    _Nomutex int query() const { return count; }
    void insert( int elem ) {
        if ( count == 20 ) _Accept( remove ); // move to main
        Elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
    }
    int remove() {
        if ( count == 0 ) _Accept( insert ); // move to main
        int elem = Elements[front];
        front = ( front + 1 ) % 20;
        count -= 1;
        return elem;
    }
  private:
    void main() {
        for ( ;; ) {          // INFINITE LOOP!!!
            _Accept( insert || remove ); // no synchronization
            _When ( count != 20 ) _Accept( insert ) {  // after call
            } or _When ( count != 0 ) _Accept( remove ) { // after call
            } // _Accept
        }
    }
};
```

- **_Accept**(m1 || m2) **S1** ≡ **_Accept**(m1) **S1**; **or _Accept**(m2) **S1**; *// S2*

  if (C1 || C2) **S1** ≡ **if** (C1) **S1**; **else if** (C2) **S1**; *// S2*
- Extended version allows different **_When**/code after call for each accept.
- The **_When** clause is like the condition of conditional critical region:
  - The condition must be true (or omitted) *and* a call to the specified member must exist before a member is accepted.
- If all the accepts are conditional and false, the statement does nothing (like **switch** with no matching **case**).
- If some conditionals are true, but there are no outstanding calls, the acceptor is blocked until a call to an appropriate member is made.
- If several members are accepted and outstanding calls exist to them, a call is selected based on the order of the **_Accept**s.
  - Hence, the order of the **_Accept**s indicates their relative priority for selection if there are several outstanding calls.

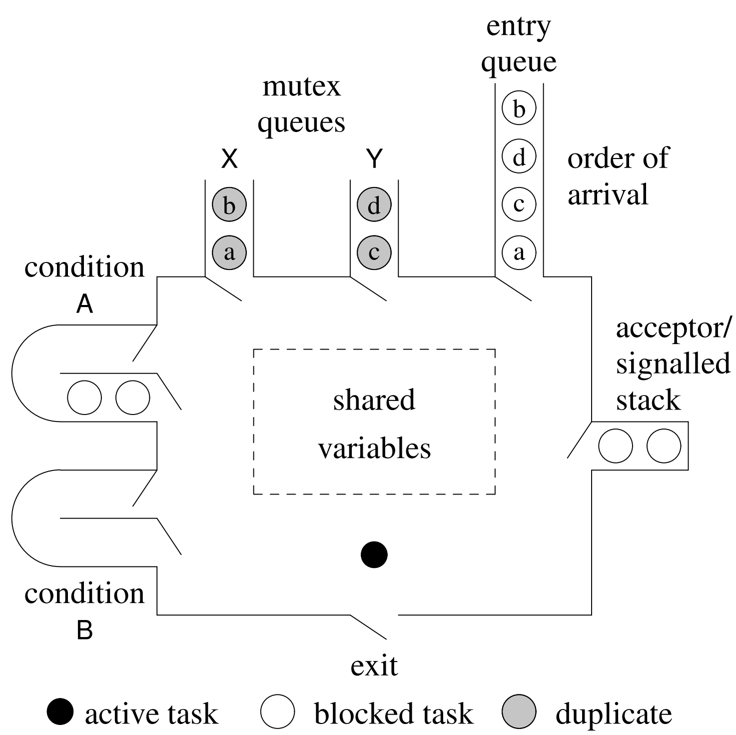
- Is there a potential starvation problem?
- Why are accept statements moved from member routines to the task main?
- Why is BoundedBuffer::main defined at the end of the task?
- Equivalence using **if** statements:

```
if ( 0 < count && count < 20 ) _Accept( insert || remove ); // not full/empty
else if ( count < 20 ) _Accept( insert ); // not full
else /* if ( 0 < count  ) */ _Accept( remove ); // not empty
```

- Generalize from 2 to 3 conditionals/members:

```
if       ( C1 && C2 && C3 ) _Accept( M1 || M2 || M3 );
else if  ( C1 && C2 ) _Accept( M1 || M2 );
else if  ( C1 && C3 ) _Accept( M1 || M3 );
else if  ( C2 && C3 ) _Accept( M2 || M3 );
else if  ( C1 ) _Accept( M1 );
else if  ( C2 ) _Accept( M2 );
else if  ( C3 ) _Accept( M3 );
```

- Necessary to ensure that for every true conditional, only the corresponding members are accepted.
- $2^N - 1$ **if** statements needed to simulate N accept clauses.
- The acceptor is pushed on the top of the A/S stack and normal implicit scheduling occurs (C < W < S).



- Once accepted call completes or caller wait()s, the statement after the accepting **_Accept** clause is executed and the accept statement is complete.

- If there is a terminating **_Else** clause and no **_Accept** can be executed immediately, the terminating **_Else** clause is executed.

```
_Accept( ... ) {
} or _Accept( ... ) {
} _Else { ... } // executed if no callers
```

  - Hence, the terminating **_Else** clause allows a conditional attempt to accept a call without the acceptor blocking.

- To achieve greater concurrency in the bounded buffer, change to:

```
    void insert( int elem ) {
        Elements[back] = elem;
    }
    int remove() {
        return Elements[front];
    }
  private:
    void main() {
        for ( ;; ) {
            _When ( count != 20 ) _Accept( insert ) {
                back = (back + 1) % 20;
                count += 1;
            } or _When ( count != 0 ) _Accept( remove ) {
                front = (front + 1) % 20;
                count -= 1;
            } // _Accept
        }
    }
```

9.2.2 Internal Scheduling

- Scheduling among tasks inside the monitor.

- As for monitors, condition, signal and wait are used.

```
_Task BoundedBuffer {
    uCondition full, empty;
    int front = 0, back = 0, count = 0;
    int Elements[20];
  public:
    _Nomutex int query() const { return count; }
    void insert( int elem ) {
        if ( count == 20 ) empty.wait();
        Elements[back] = elem;
        back = ( back + 1 ) % 20;
        count += 1;
        full.signal();
    }


    int remove() {
        if ( count == 0 ) full.wait();
        int elem = Elements[front];
        front = ( front + 1 ) % 20;
        count -= 1;
        empty.signal();
        return elem;
    }


  private:
    void main() {
        for ( ;; ) {
            _Accept( insert || remove );
            // do other work
        }
    }
};
```

- Requires combination of internal and external scheduling.

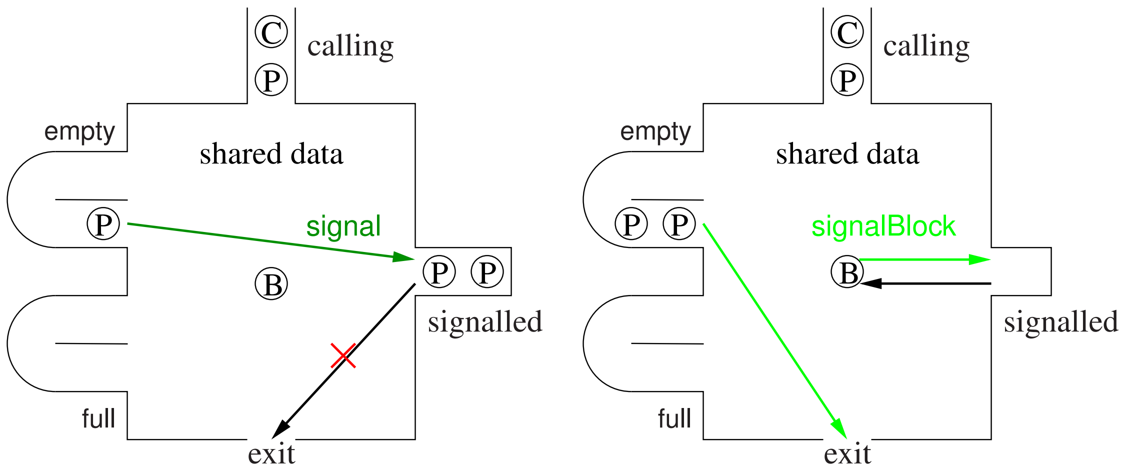
- **Rendezvous is logically pending when wait restarts _Accept task, but post _Accept statement still executed (no RendezvousFailure).**

    - Acceptor must eventually complete rendezvous for waiting caller.

- Try moving code to achieve greater concurrency.

```
    void insert( int elem ) {
        if ( count == 20 ) empty.wait();   // only wait if necessary
        Elements[back] = elem;
    }
    int remove() {
        if ( count == 0 ) full.wait();     // only wait if necessary
        return Elements[front];
    }
  private:
    void postInsert() {                    // helper members
        back = ( back + 1 ) % size;
        count += 1;
    }
    void postRemove() {
        front = ( front + 1 ) % size;
        count -= 1;
    }

    void main() {
        for ( ;; ) {
            _Accept( insert ) {
                if ( count != 20 ) {       // producer did not wait ?
                    postInsert();
                    if ( ! full.empty() ) {  // waiting consumers ?
                        full.signal();     // wake and adjust
                        postRemove();
                    }
                }

            } or _Accept( remove ) {
                if ( count != 0 ) {        // consumer did not wait ?
                    postRemove();
                    if ( ! empty.empty() ) { // waiting producers ?
                        empty.signal();    // wake and adjust
                        postInsert();
                    }
                }
            } // _Accept
        } // for
    }
```

- Must prevent starvation by producers (use **_When** or flip **_Accept** clauses).
- Must change signal to signalBlock.



- ○ Signalled tasks cannot leave because buffer task continues in monitor.
- ○ Signal-blocked tasks leave immediately because buffer-task blocks.

9.2.3 Accepting the Destructor

- Common way to terminate a task is to have a stop member:

```
_Task BoundedBuffer {
  public:
    . . .
    void stop() {} // empty
  private:
    void main() {
        // start up
        for ( ;; ) {
            _Accept( stop ) {  // terminate ?
                break;
            } or _When ( count != 20 ) _Accept( insert ) {
                . . .
            } or _When ( count != 0 ) _Accept( remove ) {
                . . .
            } // _Accept
        }
        // close down
    }
}
```

- Call stop when task is to stop:

```
int main() {
    BoundedBuffer buf;
    // create producer & consumer tasks
    // delete producer & consumer tasks
    buf.stop();  // no outstanding calls to buffer
    // maybe do something with buf (print statistics)
} // delete buf
```

- If termination and deallocation follow one another, accept destructor:

```
void main() {
    for ( ;; ) {
        _Accept( ~BoundedBuffer ) {
            break;
        } or _When ( count != 20 ) _Accept( insert ) { . . .
        } or _When ( count != 0 ) _Accept( remove ) { . . .
        } // _Accept
    }
    // close down
}
```

- However, the semantics for accepting a destructor are different from accepting a normal mutex member.
- When the call to the destructor occurs, the caller blocks immediately if there is thread active in the task because a task's storage cannot be deallocated while in use.
- When the destructor is accepted, the caller is blocked and pushed onto the A/S stack *instead of the acceptor*.
- Therefore, control restarts at the accept statement *without* executing the destructor member.
- Allows mutex object to clean up before termination (monitor or task).
- ***Task now behaves like a monitor because its thread is halted.***
- Only when the caller to the destructor is popped off the A/S stack by the implicit scheduling is the destructor executed.
- The destructor can reactivate any blocked tasks on condition variables and/or the acceptor/signalled stack.

9.3 Increasing Concurrency

- 2 task involved in direct communication: client (caller) & server (callee)
- possible to increase concurrency on both the client and server side

9.3.1 Server Side

- Server manages a resource and server thread should introduce additional concurrency (assuming no return value).

No Concurrency

```
_Task server1 {
  public:
    void mem1(...) { S1 }
    void mem2(...) { S2 }
    void main() {
        ...
        _Accept( mem1 );
        or _Accept( mem2 );
    }
}
```

Some Concurrency

```
_Task server2 {
  public:
    void mem1(...) { S1.copy−in }
    int  mem2(...) { S2.copy−out }
    void main() {
        ...
        _Accept( mem1 ) { S1.work }
        or _Accept( mem2 ) { S2.work };
    }
}
```

- No concurrency in left example as server is blocked, while client does work.
- Alternatively, client blocks in member, server does work, and server unblocks client.
- Some concurrency possible in right example if service can be factored into administrative (S1.copy) and work (S1.work) code.
  - i.e., move code from the member to statement executed after member is accepted.
- Small overlap between client and server (client gets away earlier) increasing concurrency.

9.3.1.1 Internal Buffer

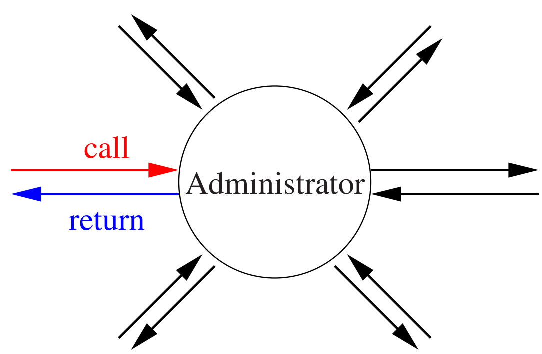
- The previous technique provides buffering of size 1 between the client and server.
- Use a larger internal buffer to allow clients to get in and out of the server faster?
- I.e., an internal buffer can be used to store the arguments of multiple clients until the server processes them.
- However, there are several issues:
  - Unless the average time for production and consumption is approximately equal with only a small variance, the buffer is either always full or empty.
  - Because of the mutex property of a task, no calls can occur while the server is working, so clients cannot drop off their arguments.

    The server could periodically accept calls while processing requests from the buffer (awkward).
  - Clients may need to wait for replies, in which case a buffer does not help unless there is an advantage to processing requests in non-FIFO order.
- Only way to free server's thread to receive new requests and return finished results to clients is add another thread.
- Additional thread is a **worker task** that calls server to get work from buffer and return results to buffer.
- Note, customer (client), manager (server) and employee (worker) relationship.

- Number of workers has to balance with number of clients to maximize concurrency (bounded-buffer problem).

9.3.1.2 Administrator

- An **administrator** is a server managing multiple clients and worker tasks.
- The key is that an administrator does little or no "real" work; its job is to manage.
- Management means delegating work to others, receiving and checking completed work, and passing completed work on.
- An administrator is called by others, so an administrator is always accepting calls.



- An administrator makes no call to another task because calling may block the administrator.
- An administrator usually maintains a list of work to pass to **worker tasks**.
- Typical workers are:

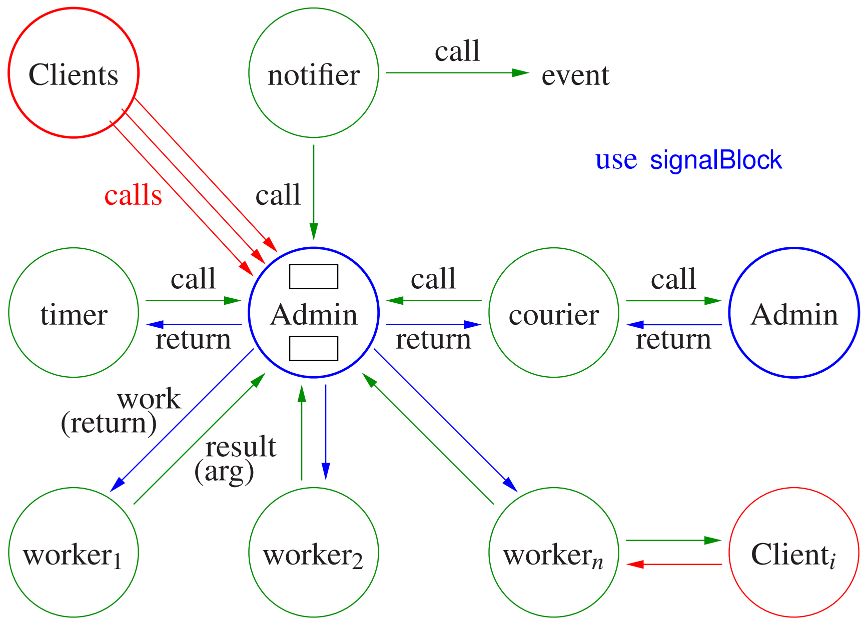
timer - prompt the administrator at specified time intervals

notifier - perform a potentially blocking wait for an external event (key press)

simple worker - do work given to them by and return the result to the administrator

complex worker - do work given to them by administrator and interact directly with client of the work

courier - perform a potentially blocking call on behalf of the administrator



9.3.2 Client Side

- While a server can attempt to make a client's delay as short as possible, not all servers do it.
- In some cases, a client may not have to wait for the server to process a request (producer/consumer problem)
- This can be accomplished by an asynchronous call from the client to the server, where the caller does not wait for the call to complete.
- Asynchronous call requires implicit buffering between client and server to store the client's arguments from the call.
- μC++ provides only synchronous call, i.e., the caller is delayed from the time the arguments are delivered to the time the result is returned (like a procedure call).
- It is possible to build asynchronous facilities out of the synchronous ones and vice versa.

9.3.2.1 Returning Values

- If a client only drops off data to be processed by the server, the asynchronous call is simple.
- However, if a result is returned from the call, i.e., from the server to the client, the asynchronous call is significantly more complex.
- To achieve asynchrony in this case, a call must be divided into two calls:

```
callee.start( arg );            // provide arguments
// caller performs other work asynchronously
result = callee.wait();         // obtain result
```

- Not same as START/WAIT because server thread exists.

- many-to-one versus one-to-one

- Time between calls allows calling task to execute asynchronously with task performing operation on the caller's behalf.

- If result is not ready when second call is made
  - caller blocks
  - caller has to call again (poll).

- However, this requires a protocol so when the client makes the second call, the correct result can be found and returned.

9.3.2.2 Tickets

- One form of protocol is the use of a token or ticket.

- The first part of the protocol transmits the arguments specifying the desired work and a ticket (like a laundry ticket) is returned immediately.

- The second call *pulls* the result by passing the ticket.

- The ticket is matched with a result, and the result is returned if available or the caller is blocks or polls until the result is available.

- However, protocols are error prone because the caller may not obey the protocol (e.g., never retrieve a result, use the same ticket twice, forged ticket).

9.3.2.3 Call-Back Routine

- Another protocol is to transmit (register) a routine on the initial call.

- When the result is ready, the routine is called by the task generating the result, passing it the result.

- The call-back routine cannot block the server; it can only store the result and set an indicator (e.g., V a semaphore) known to the client.

- The original client must *poll* the indicator or block until the indicator is set.

- The advantage is that the server can *push* the result back to the client faster (nagging the client to pickup).

- Also, the client can write the call-back routine, so they can decide to poll or block or do both.

9.3.2.4 Futures

- A **future** provides the same asynchrony as above but without an explicit protocol.
- The protocol becomes implicit between the future and the task generating the result.
- Furthermore, it removes the difficult problem of when the caller should try to retrieve the result.
- In detail, a future is an object that is a subtype of the result type expected by the caller.
- Instead of two calls as before, a single call is made, passing the appropriate arguments, and a future is returned.

```
future = callee.work( arg );          // provide arguments, return future
// perform other work asynchronously
i = future + . . .;                   // obtain result, may block if not ready
```

- The future is returned immediately and it is empty.
- The caller "believes" the call completed and continues execution with an empty result value.
- The future is filled in at some time in the "future", when the result is calculated.
- If the caller tries to use the future before its value is filled in, the caller is implicitly blocked.
- The general design for a future is:

```
class Future : public ResultType {
    friend _Task server;       // allow server to access internal state
    ResultType result;         // place result here
    uSemaphore avail;          // wait here if no result
    Future * link;             // intrusive data structure
  public:
    Future() : avail( 0 ) {}

    ResultType get() {
        avail.P();             // wait for result
        return result;
    }
};
```

  - the semaphore is used to block the caller if the future is empty
  - the link field is used to chain the future onto a server work-list.

- Unfortunately, the syntax for retrieving the value of the future is awkward as it requires a call to the get routine.
- Also, in languages without garbage collection, the future must be explicitly deleted.
- μC++ provides two forms of template futures, which differ in storage management (like Actors/Messages).

   ◦ Explicit-Storage-Management future (Future_ESM<T>) must be allocated and deallocated explicitly by the client.
   ◦ Implicit-Storage-Management future (Future_ISM<T>) automatically allocates and frees storage (when future no longer in use, GC).

- Focus on Future_ISM as simpler to use but less efficient in certain cases.
- Basic set of operations for both types of futures, divided into client and server operations.

Client

- Future value:

```
#include <uFuture.h>
Server server;                         // server thread handles async calls
Future_ISM<int> f[10];
for ( int i = 0; i < 10; i += 1 ) {
    f[i] = server.perform( i );        // asynchronous server call
}
// work asynchronously while server processes requests
for ( int i = 0; i < 10; i += 1 ) {    // retrieve async results
    osacquire( cout ) << f[i]() << ' ' << f[i]() + i << endl;
}
f[3] = 3; // DISALLOWED: OTHER THREADS READING VALUE
. . .
f[3].reset(); // reset future => empty and can be reused (be careful)
. . .
f[3].cancel(); // attempt to stop server and clients from usage
```

- After the future result is retrieved, it can be retrieved again cheaply (no blocking).
- Why is combining osacquire(cout) and f[i]() dangerous?
- Future pointer:

```
#include <uFuture.h>
Server server;                  // server thread handles async calls
int val
Future_ISM<int *> fval;
fval = server.perform( val );   // async call to server (change val by reference)
// work asynchronously while server processes requests
osacquire( cout ) << *fval() << endl;  // synchronize on retrieve value
val = 3;  // ALLOWED: BUT FUTURE POINTER IS STILL READ-ONLY
```

available – returns **true** if asynchronous call completed, otherwise **false**. complete ⇒ result available, server raised exception, or call cancelled

operator() – (function call) returns ***read-only*** copy of future result.

block if future unavailable; raise exception if exception returned by server.

future result can be retrieved multiple times by any task (⇒ read-only) until the future is reset or destroyed.

reset – mark future as empty ⇒ current future value is unavailable ⇒ future can be reused.

cancel – attempts to cancel the asynchronous call the future refers to.

Clients waiting for the result are unblocked, and exception of type uCancellation is raised at them.

cancelled – returns **true** if the future is cancelled and **false** otherwise.

Server

```
_Task Server {
    struct Work {
        int i;                          // argument(s)
        Future_ISM<int> result;         // result
        Work( int i ) : i( i ) {}
    };
    Future_ISM<int> perform( int i ) {  // called by clients
        Work *w = new Work( i );        // create work request
        requests.push_back( w );        // add to list of requests
        return w->result;               // return future in request
    }

    // server or server's worker does
    Work *w = requests.front();         // take next work request
    requests.pop_front();               // remove request
    int r = . . . w->i . . .;           // compute result using argument w->i
    w->result.delivery( r );            // insert result into future
    delete w;            // CLIENT FUTURE NOT DELETED (REF COUNTING)
};
```

delivery(T result) – copy client result into the future, unblocking clients waiting for the result.

delivery(uBaseEvent * cause) – copy exception into the future, and the exception is thrown at waiting clients.

For future to manage exception lifetime, the exception must be dynamically allocated.

```
_Exception E {};
Future_ISM<int> result;
result.delivery( new E );   // deleted by future
```

The exception is implicitly deleted when the future is deleted or reset.

Complex Future Access (client side)

- **select statement** waits for one or more **heterogeneous** futures based on logical selection-criteria.
- Simplest select statement has a single **_Select** clause, e.g.:

```
_Select( selector-expression );
```

- Selector-expression must be satisfied before execution continues.
- For a single future, the expression is satisfied if and only if the future is available.

```
_Select( f1 );                    ≡       x = f1(); // value or exception
x = f1; // value or exception
```

- Selector is only select blocked until f1.available() is true.
- Does not return future value or throw exception.
- Multiple futures may appear in a compound selector-expression, related using logical operators || and &&:

```
_Select( f1 || f2 && f3 );
```

- Normal operator precedence applies: `_Select( ( f1 || ( f2 && f3 ) ) )`.
- Execution waits until either future f1 is available or both futures f2 and f3 are available.
- Selector-expression is evaulated from left to right, even for operators of equal priority ⇒ when multiple subexpressions are true, the left-most subexpression satisfies the select statement.
- For any selector expression containing an || operator, some futures in the expression may be unavailable after the selector expression is satisfied.
- E.g., in the above, if future f1 becomes available, neither, one or both of f2 and f3 may be available.
- **or** and **and** keywords relate the **_Select** clauses like operators || and && relate futures in a select-expression, including precedence.

```
_Select( f1 || f2 && f3 );  ≡  _Select( f1 )
                               or _Select( f2 )
                               and _Select( f3 );
```

- Parentheses may be used to specify evaluation order.

```
_Select( ( f1 || ( f2 && f3 ) ) )  ≡  ( _Select( f1 )
                                       or ( _Select( f2 )
                                       and _Select( f3 ) ) );
```

- A **_Select** clause may be guarded with a logical expression and have code executed after a future receives a value:

```
_When ( conditional-expression ) _Select( f1 )
     statement-1                    // action, future available
or
     _When ( conditional-expression ) _Select( f2 )
          statement-2               // action, future available
     and _When ( conditional-expression ) _Select( f3 )
          statement-3               // action, future available
```

- Each **_Select**-clause action is executed when its sub-selector expression is satisfied, i.e., when each future becomes available.
- However, control does not continue until the selector expression associated with the entire statement is satisfied.
- E.g., if f2 becomes available, statement-2 is executed but the selector expression for the entire statement is **not** satisfied so control blocks again.
- When either f1 or f3 become available, statement-1 or 3 is executed, and the selector expression for the entire statement is satisfied so control continues.
- If a guard is false, execution continues without waiting for that future to become available.

```
_When( true ) _Select( f1 ) {...}             _When( true ) _Select( f1 ) {...}
or                                            or
     _When( false ) _Select( f2 ) {...}  ≡
     and
     _When( true ) _Select( f3 ) {...}             _When( true ) _Select( f3 ) {...}
```

  Assume only f3 becomes available, execution continues.

- An action statement is triggered only once for its selector expression, even if the selector expression is compound.

```
_Select( f1 )
     statement-1
or _Select( f2 && f3 )
     statement-2                // triggered once after both available
```

- In statement-2, both futures f2 and f3 are available.
- However, for ||:

```
_Select( f1 || f2 )
     statement-1                // triggered once after one available
and _Select( f3 )
     statement-2
```

- In statement-1, only one future f1 or f2 caused the action to be triggered.
- Hence, it is necessary to check which of the two futures is available.

- A select statement can be non-blocking using a terminating **_Else** clause, e.g.:

```
_Select( selector-expression )
    statement                          // action
_When ( conditional-expression ) _Else   // terminating clause
    statement                          // action
```

- The **_Else** clause *must* be the last clause of a select statement.
- If its guard is true or omitted and the select statement is not immediately true, then the action for the **_Else** clause is executed and control continues.
- If the guard is false, the select statement blocks as if the **_Else** clause is not present.
- Complex synchronization: wait for 3 different events or 1 to stop.

```
Future_ISM<int> fi;
Future_ISM<double> fd;
struct Msg { int i, j; }; Future_ISM<Msg> fm;
struct Stop {}; Future_ISM<Stop> fs;
struct Cont {}; Future_ISM<Cont> fc;
_Task Worker {
    void main() {
        for ( ;; ) {
            _Select( fi ) { cout << fi() << endl; fi.reset(); }
            and _Select( fd ) { cout << fd() << endl; fd.reset(); }
            and _Select( fm ) { cout << fm()->i << " "
                                << fm()->j << endl; fm.reset(); }
            or _Select( fs ) { cout << "stop" << endl; break; }
            fc.delivery( (Cont){} );          // synchronize
        }
    }
};
int main() {
    Worker worker;
    for ( int i = 0; i < 10; i += 1 ) {
        fi.delivery( i );
        fd.delivery( i + 2.5 );
        fm.delivery( (Msg){ i, 2 } );
        fc(); fc.reset();                 // wait for 3 futures to be processed
    }
    fs.delivery( (Stop){} );
} // wait for worker to terminate
```

10 Optimization

- A computer with infinite memory and speed requires no optimizations to use less memory or run faster (space/time).
- With finite resources, optimization is useful/necessary to conserve resources and for good performance.
- Furthermore, most programs are not written in optimal order or in minimal form.
  - OO, Functional, SE are seldom optimal approaches on von Neumann machine.
- General forms of optimizations are:
  - **reordering**: data and code are reordered to increase performance in certain contexts.
  - **eliding**: removal of unnecessary data, data accesses, and computation.
  - **replication**: processors, memory, data, code are duplicated because of limitations in processing and communication speed (speed of light).
- Optimized program must be isomorphic to original ⇒ produce same result for fixed input.
- Kinds of optimizations are restricted by the kind of execution environment.

10.1 Sequential Optimizations

- Most programs are sequential; even concurrent programs are
  - (large) sections of sequential code per thread connected by
  - small sections of concurrent code where threads interact (protected by synchronization and mutual exclusion (SME))
- ***Sequential*** execution presents simple semantics for optimization.
  - operations occur in **program order**, i.e., sequentially
- Dependencies result in partial ordering among a set of statements (precedence graph):
  - **data dependency** (R ⇒ read, W ⇒ write)

$R_x \rightarrow R_x$	$W_x \rightarrow R_x$	$R_x \rightarrow W_x$	$W_x \rightarrow W_x$
`y = x;`	`x = 0;`	`y = x;`	`x = 0;`
`z = x;`	`y = x;`	`x = 3;`	`x = 3;`

    Which statements can be reordered?
  - **control dependency**

    ```
    1   if ( x == 0 )
    2       y = 1;
    ```

    Statements cannot be reordered as line 1 determines if 2 is executed.

- To achieve better performance, compiler/hardware make changes:

  1. reorder disjoint (independent) operations (**variables have different addresses**)

$R_x \rightarrow R_y$	$W_x \rightarrow R_y$	$R_x \rightarrow W_y$	$W_x \rightarrow W_y$
`t = x;`	`x = 0;`	`x == 1;`	`y = 0;`
`s = y;`	`y == 1;`	`y = 3;`	`x = 3;`

     Which statements can be reordered?

  2. elide unnecessary operations (transformation/dead code)

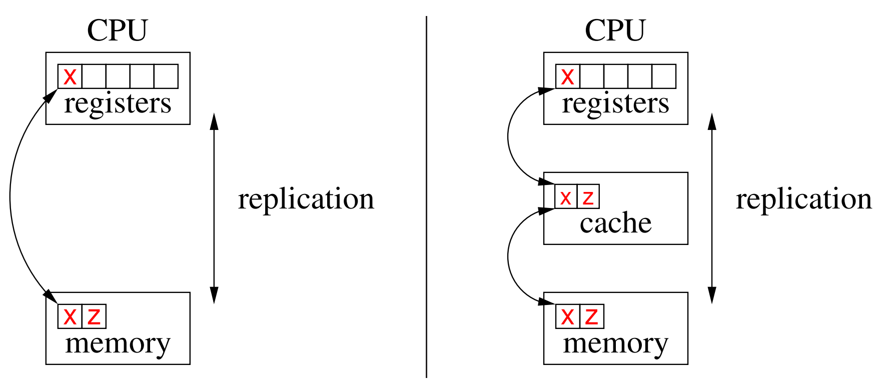
```
x = 0;  // unnecessary, immediate change
x = 3;

for ( int i = 0; i < 10000; i += 1 ); // unnecessary, no loop body

int factorial( int n, int acc ) {  // tail recursion
    if (n == 0) return acc;
    return factorial( n - 1, n * acc ); // convert to loop
}
```

  3. execute in parallel if multiple functional-units (adders, floating units, pipelines, cache)

- Very complex reordering, reducing, and overlapping of operations allowed.
- Overlapping implies micro-parallelism, ***but limited capability in sequential execution.***

10.2 Memory Hierarchy

- Complex memory hierarchy:

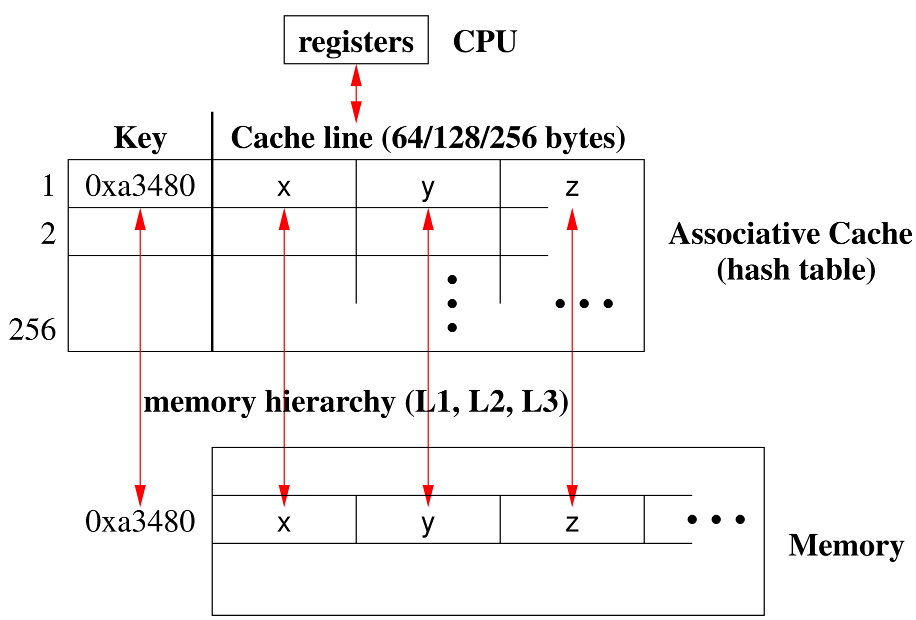


- Optimizing data flow along this hierarchy defines a computer's speed.
- Hardware aggressively optimizes data flow for sequential execution.
- Having basic understanding of cache is essential to understanding performance of both sequential and concurrent programs.

10.2.1 Cache Review

- Problem: CPU 100(0) times faster than memory (100,00(0) times faster than disk).
- Solution: copy data from general memory into very, very fast local-memory (registers).
- Problem: billions of bytes of memory but only 6–256 registers.
- Solution: move highly accessed data ***within*** a program from memory to registers for as long as possible and then back to memory.
- Problem: quickly run out of registers as more data accessed.
  - ⇒ must rotate data from memory through registers dynamically.
  - compiler attempts to keep highly used variables in registers (LRU, requires oracle)
- Problem: does not handle highly accessed data ***among*** programs (threads).
  - each context switch saves and restores most registers to memory
  - registers are private and cannot be shared
- Solution: use hardware **cache** (automatic registers) to stage data without pushing to memory and allow sharing of data among programs.

```
int x, y, z;
x += 1;      ld   r1,0xa3480      // load register 1 from x
             add  r1,#1           // increment
             st   r1,0xa3480      // store register 1 to x
```



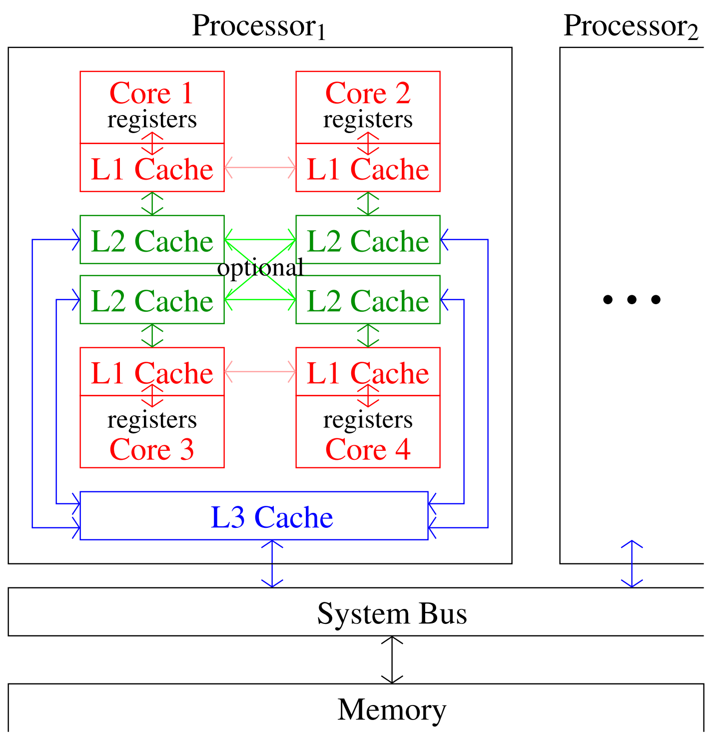
  - Caching transparently hides the latency of accessing main memory.
  - Cache loads in 64/128/256 bytes, called **cache line**, with addresses multiple of line size.

  - When x is loaded into register 1, a cache line containing x, y, and z are implicitly copied up the memory hierarchy from memory through caches.
  - When cache is full, data evicted, i.e., remove old cache-lines to bring in new (LRU).
  - When program ends, its addresses are flushed from the memory hierarchy.

- In theory, cache can eliminate registers, but registers provide small addressable area (register window) with short addresses (3-8 bits for 8-256 registers) ⇒ shorter instructions.

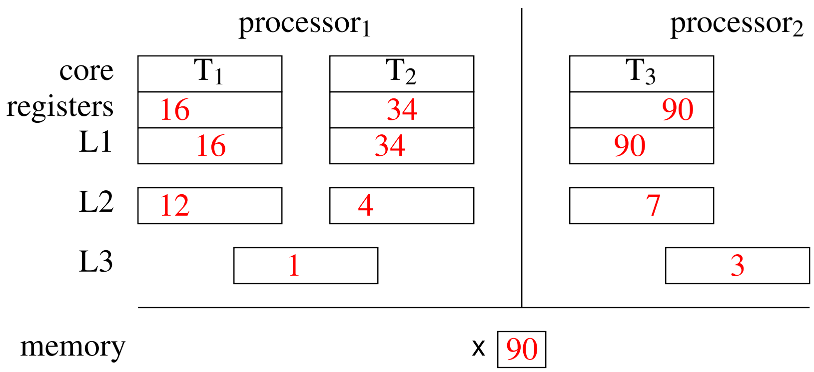
10.2.2 Cache Coherence

- Multi-level caches used, each larger but with diminishing speed (and cost).
- E.g., 64K L1 cache (32K Instruction, 32K Data) per core, 256K L2 cache per core, and 8MB L3 cache shared across cores.

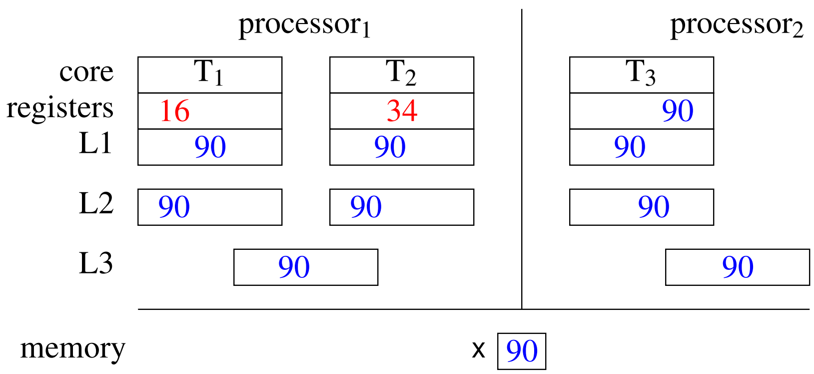


- Data reads logically percolate variables from memory up the memory hierarchy, making cache copies, to registers.
- Why is it necessary to eagerly move reads up the memory hierarchy?
- Data writes from registers to variables logically percolate down the memory hierarchy through cache copies to memory.
- Why is it advantageous to lazily move writes down the memory hierarchy?
- If OS moves program to another processor, all caching information is invalid and the program's data-hierarchy reforms.

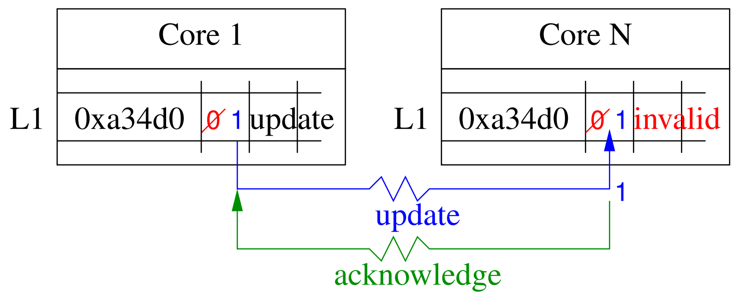
- Unlike registers, *all* cache values are shared across the computer.
- Hence, variable can be replicated in a large number of locations.
- Without cache coherence for shared variable x (madness)



- With cache coherence (snooping or directory-based) for shared variable x



- **Cache coherence** is hardware protocol ensuring update of duplicate data.
- **Cache consistency** addresses ***when*** processor sees update ⇒ bidirectional synchronization.
- **Prevent flickering and scrambling during simultaneous R/W or W/W.**



- Eager cache-consistency means data changes appear instantaneous by waiting for acknowledge from all cores (complex/expensive).

- Lazy cache-consistency allows reader to see own write before acknowledgement ⇒ **concurrent programs read stale data!**
  - writes eventually appear in (largely) same order as written
  - critical section works as writes to shared variable appear before write to lock release
  - otherwise, spin (lock) until write appears
- If threads continually read/write same memory locations, they invalidate duplicate cache lines, resulting in excessive cache updates.
  - called **cache thrashing**
  - updated value bounces from one cache to the next
- Because cache line contains multiple variables, cache thrashing can occur inadvertently, called **false sharing**.
- Thread 1 read/writes x while Thread 2 read/writes y ⇒ no direct shared access, but indirect sharing as x and y share cache line.
  - Fix by separating x and y with sufficient storage (padding) to be in next cache line.
  - Difficult for dynamically allocated variables as memory allocator positions storage.

    ```
    thread 1                          thread 2
    int *x = new int                  int *y = new int;
    ```

    x and y may or may not be on same cache line.

10.3 Concurrent Optimizations

- In sequential execution, **strong memory ordering**: reading always returns last value written.
- In concurrent execution, **weak memory ordering**: reading can return previously written value or value written in future.
  - happens on multi-processor because of scheduling and buffering (see scrambling/-flickering in Section 5.18.6, p. 89 and freshness/staleness in Section 6.4.4.4, p. 128).
  - notion of ***current*** value becomes blurred for shared variables unless everyone can see values assigned simultaneously.
- SME control order and speed of execution, otherwise non-determinism causes random results or failure (e.g., race condition, Section 7.1, p. 137).
- Sequential sections accessing private variables can be optimized normally ***but not across concurrent boundaries***.
- Concurrent sections accessing shared variables can be corrupted by sequential optimizations ⇒ restrict optimizations to ensure correctness.
- For correctness and performance, identify concurrent code and only restrict *its* optimization.

- What/how to restrict depends on what sequential assumptions are implicitly applied by hardware and compiler (programming language).
- Following examples show how sequential optimizations cause failures in concurrent code.

10.3.1 Disjoint Reordering

- $R_x \rightarrow R_y$ allows $R_y \rightarrow R_x$

  Reordering disjoint reads does not cause problems. Why?

- $W_x \rightarrow R_y$ allows $R_y \rightarrow W_x$
  - In Dekker entry protocol (see Section 5.18.6, p. 89)

```
1   me = WantIn; // W
2   while ( you == WantIn ) { // R
3       . . .
```

```
    temp = you; // R
1   me = WantIn; // W
2   while ( temp == WantIn ) {
3       . . .
```

  both threads read DontWantIn, both set WantIn, both see DontWantIn, and proceed.

- $R_x \rightarrow W_y$ allows $W_y \rightarrow R_x$
  - In synchronization flags (see Section 5.12, p. 83), allows interchanging lines 1 & 3 for Cons:

```
        Cons
1   while ( ! Insert ); // R
2   Insert = false;
3   data = Data; // W
```

```
        Cons
3   data = Data; // W
1   while ( ! Insert ); // R
2   Insert = false;
```

  allows reading of uninserted data

- $W_x \rightarrow W_y$ allows $W_y \rightarrow W_x$
  - In synchronization flags (see Section 5.12, p. 83), allows interchanging lines 1 & 2 in Prod and lines 3 & 4 in Cons:

```
        Prod
1   Data = i; // W
2   Insert = true; // W
```

```
        Prod
2   Insert = true; // W
1   Data = i; // W
```

  allows reading of uninserted data

  - In Peterson's entry protocol, allows interchanging lines 1 & 2 (see Section 5.18.7, p. 91):

```
1   me = WantIn; // W
2   ::Last = &me; // W
```

```
2   ::Last = &me; // W
1   me = WantIn; // W
```

  allows race before either task sets its intent and both proceed

- Compiler uses all of these reorderings to break mutual exclusion:

```
lock.acquire()          // critical section      lock.acquire()
// critical section     lock.acquire()           lock.release();
lock.release();         lock.release();          // critical section
```

- moves lock entry/exit after/before critical section because entry/exit variables not used in critical section.
- E.g., **double-check locking** for singleton-pattern:

```
int * ip = nullptr;              // shared (volatile for correctness)
...
if ( ip == nullptr ) {           // no storage ?
    lock.acquire();              // attempt to get storage (race)
    if ( ip == nullptr ) {       // still no storage ? (double check)
        ip = new int( 0 );       // obtain and initialize storage
    }
    lock.release();
}
```

Why do the first check? Why do the second check?

- Fails if last two writes are reordered, W_{malloc} and W_{ip}, disjoint variables:

```
call   malloc     // new storage address returned in r1
st     #0,(r1)    // initialize storage
st     r1,ip      // initialize pointer
```

see ip but uninitialized.

10.3.2 Eliding

- For high-level language, compiler decides when/which variables are loaded into registers and for how long.
- Elide reads (loads) by copying (replicating) value into a register:

```
    Task1                        Task2
...                          register = flag; // one read, auxiliary variable
flag = false // write        while ( register ); // cannot see change by T1
```

- Hence, variable logically disappears for duration in register.
- ⇒ task spins forever in busy loop if R before W.
- Also, elide meaningless sequential code:

```
sleep( 1 ); // unnecessary in sequential program
```

⇒ task misses signal by not delaying

10.3.3 Replication

- Why is there a benefit to reorder R/W?
- Modern processors increase performance by executing multiple instructions in parallel (data flow, precedence graph (see 6.4.1)) on **replicated hardware**.
  - internal pool of instructions taken from program order
  - begin simultaneous execution of instructions with inputs

- ◦ collect results from finished instructions
- ◦ feed results back into instruction pool as inputs
- ◦ ⇒ instructions with independent inputs execute out-of-order

- From sequential perspective, disjoint reordering is ***unimportant***, so hardware starts many instruction simultaneously.
- From concurrent perspective, disjoint reordering is ***important***.

10.4 Memory Model

- Manufacturers define set of optimizations performed implicitly by processor.
- Set of optimizations indirectly define a **memory model**.

Relaxation Model	W → R	R → W	W → W	Lazy cache update
atomic consistent (AT)				
sequential consistency (SC)				√
total store order (TSO)	√			√
partial store order (PSO)	√	√		√
weak order (WO)	√	√	√	√
release consistency (RC)	√	√	√	√

- AT has events occur instantaneously ⇒ slow or impossible (distributed).
- SC accepts all events cannot occur instantaneously ⇒ may read old values
- SC still strong enough for software mutual-exclusion (Dekker 5.18.6 / Peterson 5.18.7).
  - ◦ SC often considered minimum model for concurrency (Java provides SC)
- No hardware supports just AT/SC.
  - ◦ TSO (x86/SPARC), PSO, WO (ARM, Alpha), RC (PowerPC)

10.5 Preventing Optimization Problems

- All optimization problems result from races on shared variables.
- If shared data is protected by locks (implicit or explicit),
  - ◦ locks define the sequential/concurrent boundaries,
  - ◦ boundaries must preclude optimizations that affect concurrency.
- Called **race free** as synchronization and mutual exclusion preclude races.
- However, race free does have races.

- Races are internal to locks, which lock programmer must deal with.
- Two approaches:
  - ad hoc: programmer manually augments all data races with pragmas to restrict compiler/hardware optimizations: not portable but often optimal.
  - formal: language has memory model and mechanisms to abstractly define races in program: portable but often baroque and suboptimal.
- data access / compiler (C/C++): **volatile** qualifier
  - Force variable loads and stores to/from registers (at **sequence points**)
  - created for longjmp or force access for memory-mapped devices
  - for architectures with few registers, practically all variables are implicitly volatile. Why?
  - Java **volatile** / C++11 atomic stronger ⇒ prevent eliding ***and*** disjoint reordering.
- program order / compiler (static): disable inlining, **asm**("" ::: "memory");
- memory order / runtime (dynamic): sfence, lfence, mfence (x86)
  - guarantee previous stores and/or loads are completed, before continuing.
- atomic operations test-and-set, which often imply fencing
- cache is normally invisible and does not cause issues (except for DMA)
- mechanisms to fix issues are specific to compiler or platform
  - difficult, low-level, diverse semantics, not portable ⇒ ***tread carefully!***
- Dekker for TSO:

```
#define CALIGN __attribute__(( aligned (64) )) // cache-line alignment
#define Pause() __asm__ __volatile__ ( "pause" : : : ) // efficient busy wait
#define Fence() __asm__ __volatile__ ( "mfence" ) // prevent hardware reordering
#include <atomic>
enum Intent { DontWantIn, WantIn } * Last;
_Task Dekker {
    volatile Intent / std::atomic<Intent> & me, & you, *& Last;

    void main() {
        for ( int i = 1; i <= 1000; i += 1 ) {
            for ( ;; ) {                    // entry protocol
                me = WantIn;                // high priority
                Fence();
              if ( you == DontWantIn ) break;
                if ( Last == &me ) {        // high priority ?
                    me = DontWantIn;
                    while ( Last == &me ) Pause();  // low priority
                }
                Pause();
            }
            CriticalSection();              // critical section
            Last = &me;                     // exit protocol
            me = DontWantIn;
        }
    }
  public:
    Dekker( volatile Intent & me, volatile Intent & you, volatile Intent *& Last ) :
        me(me), you(you), Last(Last) {}
};
int main() {
    volatile Intent me CALIGN = DontWantIn, you CALIGN = DontWantIn,
            *Last CALIGN = rand() % 2 ? &me : &you;
    Dekker t0(me, you, Last), t1(you, me, Last);
};
```

- C++ atomic automatically fences shared variables, but can be suboptimal.
- Locks built with these features ensure SC for protected shared variables.
  - **no user races and strong locks ⇒ SC memory model**

11 Other Approaches

11.1 Atomic (Lock-Free) Data-Structure

- **Lock free** data-structure have operations, which are critical sections, but performed without **ownership**.
  - e.g., add/remove node without any blocking duration (operation takes constant atomic time)
- Lock-free is still locking (misnomer) ⇒ spin for conceptual lock ⇒ busy-waiting (starvation).
- If guarantees eventual progress, called **wait free**.

11.1.1 Compare and Set Instruction

- The compare-and-set(assign) instruction performs an atomic compare and conditional assignment CAS (erroneously called compare-and-swap).

```
int Lock = OPEN; // shared
```

```
bool CAS( int & val,
  int comp, int nval ) {
    // begin atomic
    if ( val == comp ) {
        val = nval;
        return true;
    }
    return false;
    // end atomic
}
```

```
void Task::main() { // each task does
    while ( ! CAS( Lock, OPEN, CLOSED ) );
    // critical section
    Lock = OPEN;
}
```

  - if compare/assign returns true ⇒ loop stops and lock is set to closed
  - if compare/assign returns false ⇒ loop executes until the other thread sets lock to open
  - Alternative implementation assigns comparison value with the value when not equal.

```
bool CAV( int & val, int & comp, int nval ) {
    // begin atomic
    if (val == comp) {
        val = nval;
        return true;
    }
    comp = val;              // return changed value
    return false;
    // end atomic
}
```

  - Assignment when unequal useful to restart operations with new changed value.

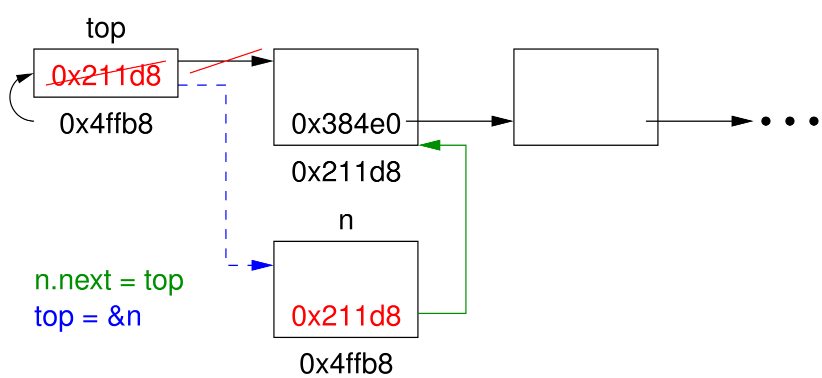
11.1.2 Lock-Free Stack

- E.g., build a stack with lock-free push and pop operations.

```
class Stack {
    Node * top;             // pointer to stack top
  public:
    struct Node {
        // data
        Node * next;        // pointer to next node
    };
    void push( Node & n );
    Node * pop();
};
```

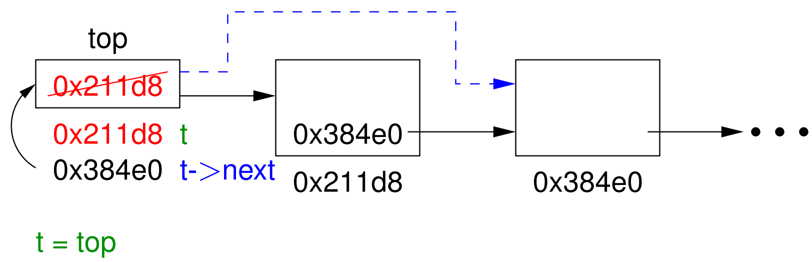
- Use CAS to atomically update top pointer when nodes pushed or popped concurrently.

```
void Stack::push( Node & n ) {
    for ( ;; ) {                    // busy wait
        n.next = top;               // link new node to top node
      if ( CAS( top, n.next, &n ) ) break; // attempt to update top node
    } //            top = &n
}
```



- Create new node, n, at 0x4ffb8 to be added.
- Set n.next to top.
- CAS tries to assign new top &n to top.
- CAS fails if top changed since copied to n.next
- If CAS failed, update n.next to top, and try again.
- CAS succeeds when top == n.next, i.e., no push or pop between setting n.next and trying to assign &n to top.
- CAV copies changed value to n.next, so eliminates resetting t = top in busy loop.

```
Node * Stack::pop() {
     Node * t;
     for ( ;; ) {                    // busy wait
          t = top;                   // copy current top
       if ( t == nullptr ) return t; // empty list ?
       if ( CAS( top, t, t->next ) ) return t; // attempt to update top node
     } //          top = t->next
}
```



- Copy top node, 0x4ffb8, to t for removal.
- If not empty, attempt CAS to set new top to next node, t->next.
- CAS fails if top changed since copied to t.
- If CAS failed, update t to top, and try again.
- CAS succeeds when top == t->next, i.e., no push or pop between setting t and trying to assign t->next to top.
- CAV copies the changed value into t, so eliminates resetting t = top in busy loop.

• Note, load of top->next can access stolen node, and fail if storage freed and address-space shortened.

11.1.3 ABA problem

• Pathological failure for series of pops and pushes, called **ABA problem**.

• Given stack with 3 nodes:

top → A → B → C

• Popping task, T_i, sets t to A and dereferenced t->next to get next node B for argument to CAS.

• T_i is now time-sliced **before the CAS**, and while blocked, nodes A and B are popped, and A is pushed again:

top → A → C   *// B is gone!*

• When T_i restarts, CAS successfully removes A as same header before time-slice.

- ***But now incorrectly sets* top *to its next node* B*:***

  top → B → ???

  stack is now corrupted!!!

11.1.4 Hardware Fix

- Probabilistic solution for stack exists using double-wide CAVD instruction, which compares and assigns 64/128-bit values for 32/64-bit architectures.

```
bool CAVD( uintS_t &val, uintS_t &comp, uintS_t nval ) {
    // begin atomic
    if ( val == comp ) {        // 64/128-bit compare
        val = nval;             // 64/128-bit assignment
        return true;
    }
    comp = val;                 // 64/128-bit assignment
    return false;
    // end atomic
}
```

- Now, associate counter (ticket) with header node:

```
class Stack {
    union Link {
        struct {                // 32/64-bit x 2
            Node * top;         // pointer to stack top
            uintptr_t count;    // count each push
        };
        uintS_t atom;           // 64/128-bit integer
    } link;
  public:
    struct Node {
        // resource data
        Link next;              // pointer to next node/count (resource)
    };
    Stack() { link.atom = 0; }
    void push( Node & n );
    Node * pop();
};
```

- Increment counter in push (**only count pushes**) so pop can detect ABA if node re-pushed.

```
void Stack::push( Node & n ) {
    n.next = link;              // atomic assignment unnecessary
    for ( ;; ) {                // busy wait
      if ( CAVD( link.atom, n.next.atom,
              (Link){ &n, n.next.count + 1 }.atom ) ) break;
    } //          link.top = &n, link.count = n.next.count + 1
}
```

- CAVD used to copy entire header to n.next, as structure assignment (2 fields) is not atomic.
- In busy loop, copy local idea of top to next of new node to be added.
- CAVD tries to assign new top-header to (h).
- If top has not changed since copied to n.next, update top to n (new top), and ***increment counter***.
- If top has changed, CAVD copies changed values to n.next, so try again.

```
Node * Stack::pop() {
    Link t = link;                    // atomic assignment unnecessary
    for ( ;; ) {                      // busy wait
      if ( t.top == nullptr ) return nullptr; // empty stack ?
      if ( CAVD( link.atom, t.atom,
              (Link){ t.top->next.top, t.count }.atom ) ) return t.top;
    } //           link.top = t.top->next.top, link.count = t.count
}
```

- CAVD used to copy entire header to t, as structure assignment (2 fields) is not atomic.
- In busy loop, check if pop on empty stack and return **nullptr**.
- If not empty, CAVD tries to assign new top t.top->next.top,t.count to h.
- If top has not changed since copied to t, update top to t.top->next.top (new top).
- If top has changed, CAVD copies changed values to t, so try again.

- ABA problem (mostly) fixed:

  top,3 → A → B → C

- Popping task, T_i, has t set to A,3 and dereferenced B from t.top->next in argument of CAVD.
- T_i is time-sliced, and while blocked, nodes A and B are popped, and A is pushed again:

  top,4 → A → C   *// adding A increments counter*

- When T_i restarts, CAVD fails as header A,3 not equal top A,4.
- Only probabilistic correct as counter finite (like ticket counter).
  - task T_i is time-sliced and sufficient pushes wrap counter to value stored in T_i's header,
  - node A just happens to be at the top of the stack when T_i unblocks.
  - doubtful if failure arises, given 32/64-bit counter and pathological case.
- Finally, none of the programs using CAS ensure eventual progress; therefore, rule 5 is broken.

11.1.5 Hardware/Software Fix

- Fixing ABA with CAS/V and more code is extremely complex (100s of lines of code), as is implementing more complex data structures (queue, deque, hash).
- All solutions require complex determination of when a node has no references (like garbage collection).
  - each thread maintains a list of accessed nodes, called **hazard pointers**
  - thread updates its hazard pointers while other threads are reading them
  - thread removes a node by hiding it on a private list and periodically scans the hazard lists of other threads for references to that node
  - if no pointers are found, the node can be freed
- For lock-free stack: x, y, z are memory addresses
  - first thread puts x on its hazard list
  - second thread cannot reuse x, because of hazard list
  - second thread must create new object at different location
  - first thread detects change
- Summary: locks versus lock-free
  - lock-free has no ownership (hold-and-wait) ⇒ no deadlock
  - lock-free can only handle limited set of critical sections
    lock can protect arbitrarily complex critical section versus
  - lock-free no panacea, performance unclear
  - combine lock and lock-free?

11.2 Exotic Atomic Instruction

- VAX computer has instructions to atomically insert and remove a node to/from the head or tail of a circular doubly linked list.

```
struct links {
    links *front, *back;
}
bool INSQUE( links &entry, links &pred ) {      // atomic execution
    // insert entry following pred
    return entry.front == entry.back;           // first node inserted ?
}
bool REMQUE( links &entry ) {                   // atomic execution
    // remove entry
    return entry.front == null;                 // last node removed ?
}
```

- MIPS processor has two instructions that generalize atomic read/write cycle: LL (load locked) and SC (store conditional).
  - LL instruction loads (reads) a value from memory into a register, and sets a hardware **reservation** on the memory from which the value is fetched.
  - Register value can be modified, even moved to another register.
  - SC instruction stores (writes) new value back to original or another memory location.
  - However, store is conditional and occurs only if no interrupt, exception, or write has occurred at LL reservation.
  - Failure indicated by setting the register containing the value to be stored to 0.
  - E.g., implement test-and-set with LL/SC:

```
int testSet( int &lock ) {      // atomic execution
    int temp = lock;            // read
    lock = 1;                   // write
    return temp;                // return previous value
}
testSet:                        // register $4 contains pointer to lock
    ll   $2,($4)                // read and lock location
    or   $8,$2,1                // set register $8 to 1 (lock | 1)
    sc   $8,($4)                // attempt to store 1 into lock
    beq  $8,$0,testSet          // retry if interference between read and write
    j    $31                    // return previous value in register $2
```

  - Does not suffer from ABA problem.

```
Node *pop( Header &h ) {
    Node *t, next;
    for ( ;; ) {                // busy wait
        t = LL( top );
      if ( t == nullptr ) break;  // empty list ?
        next = t->next
      if ( SC( top, next ) ) break;  // attempt to update top node
    }
    return t;
}
```

  - SC detects any ***change*** to top, whereas CAS only detects a specific value change to top (is top not equal to A).
  - However, most architectures support weak LL/SC.
    - reservation granularity may be cache line or memory block rather than word
    - no nesting or interleaving of LL/SC pairs, and prohibit memory access between LL and SC.
  - Cannot implement atomic swap of 2 memory locations as two reservations are necessary (register to memory swap is possible).
- Hardware transactional memory allows 4, 6, 8 reservations, e.g., Advanced Synchronization Facility (ASF) proposal in AMD64.

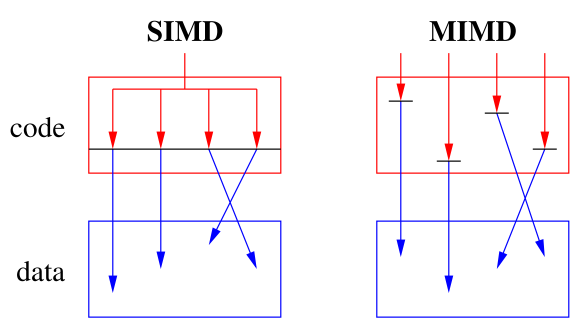
- Like database **transaction** that optimistically executes change, and either commits changes, or rolls back and restarts if interference.
  - SPECULATE : start speculative region and clear zero flag ; next instruction checks for abort and branches to retry.
  - LOCK : MOV instructions indicates location for atomic access, but moves not visible to other CPUs.
  - COMMIT : end speculative region
    - if no conflict, make MOVs visible to other CPUs.
    - if conflict to any move locations, set failure, discard reservations and restore registers back to instruction following SPECULATE
- Can implement several data structures without ABA problem.
- Software Transactional Memory (STM) allows any number of reservations.
  - atomic blocks of arbitrary size:

```
void push( header & h, node & n ) {
    atomic {                    // SPECULATE
        n.next = top;           // LOCK/MOV
        top = &n
    }                           // COMMIT
}
```

  - records all memory locations read and written, and all values mutated.
    - bookkeeping costs and rollbacks typically result in performance degradation
  - alternative implementation inserts locks to protect shared access
    - finding all access is difficult and ordering lock acquisition is complex

11.3 General-Purpose GPU (GPGPU)

- Graphic Processing Unit (GPU) is a **coprocessor** to main computer, with separate memory and processors.
- GPU is a Single-Instruction Multiple-Data(Thread) (SIMD(T)) architecture versus Multiple-Instruction Multiple-Data (MIMD)



- SIMD occurs at instruction level, e.g., `i &= 0x34fe256`.

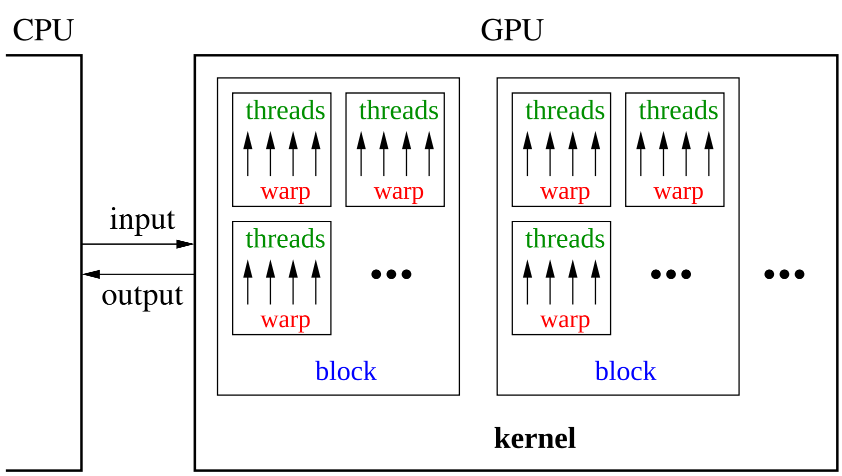
```
ld  r3, i
and r3, 0x34fe256
st  r3, i
```

  Does not loop 64 times "anding" each bit; 64 parallel "ands" are done simultaneously.

- Can `i += 1` be SIMD at the instruction level?
- Problems in branching code

```
if ( a[i] % 2 == 0 ) {
    a[i] /= 2;           // true threads
} else {
    a[i] += 3;           // false threads
}
```

- All threads test the condition (create mask of true and false)
  - true threads execute "then" instructions, false threads execute NOP (no-operation)
  - false threads execute "else" instructions, true threads execute NOP
- In general, critical path is time to execute both clauses of **if** (no speedup).
- Complex contortions to eliminate different forms of branching.
- GPU structure
  - **kernel** manages multiple blocks (loaded/controlled by CPU)
  - **block** executes the same code
  - **warp** synchronizes execution (one instruction decoder per warp)
  - **thread** computes value

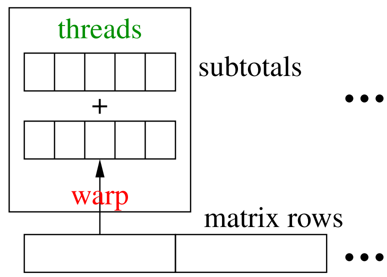


  - blocks may be barrier-synchronized
  - synchronization among blocks ⇒ finishing kernel and launching new one

- Instead of cache to optimize latency in warp, large register file is used to optimize throughput.
  - GPUs have enough duplicate registers to store state of several warps.
- Kernel is memory-bound ⇒ data layout extremely important performance consideration.

```
// kernel routine, handle contiguous matrix, different ID for each thread
kernel void GPUsum( float *matrix[ ], float subtotals[ ], int rows ) {
#   define sub(m, r, c) ((typeof(m[0][0]) *)m)[r * rows + c]
    subtotals[ID] = 0.0;
    for ( int r = 0; r < rows; r += 1 )
        subtotals[ID] += sub( matrix, r, ID );
}
```

- Add rows by columns.



- Warps scheduled to run when their required data is loaded from memory.
- CPU sets up GPU memory, loads memory, launches code, retrieves results.

```
int main() {
    int rows, cols;
    cin >> rows >> cols;        // matrix size
    // optimal to use contiguous matrix
    float matrix[rows][cols], subtotals[rows], total = 0.0;
    // . . . fill matrix
    float * matrix_d, * subtotals_d;          // matrix/subtotals buffer on GPU
    // allocate space on GPU
    GPUMalloc( &matrix_d, sizeof(matrix) );
    GPUMalloc( &subtotals_d, sizeof(subtotals) );
    // copy matrix to GPU
    GPUMemcpy( matrix_d, matrix, sizeof(matrix), GPUMemcpyHostToDevice );
    // compute matrix sum on GPU
    GPUsum<<< 1, cols >>>( matrix_d, substotals_d, rows );
    // do asynchronous work!!!
    // copy subtotals from GPU, may block
    GPUMemcpy( subtotals, subtotals_d, sizeof(subtotals), GPUMemcpyDeviceToHost );
    for ( int i = 0; i < cols; i += 1 ) total += subtotals[i];
    cout << total << endl;
}
```

- Most modern multi-core CPUs have similar model using vector-processing.
  - Simulate warps and use concurrency framework (μC++) to schedule blocks.

11.4 Concurrency Languages

11.4.1 Ada 95

- E.g., monitor bounded-buffer, restricted implicit (automatic) signal:

```
protected type buffer is  -- _Monitor
    entry insert( elem : in ElemType ) when count < Size is  -- mutex member
    begin
        -- add to buffer
        count := count + 1;
    end insert;
    entry remove( elem : out ElemType ) when count > 0 is  -- mutex member
    begin
        -- remove from buffer, return via parameter
        count := count - 1;
    end remove;
  private:
    ... // buffer declarations
    count : Integer := 0;
end buffer;
```

- The **when** clause is only be used at start of entry routine not within.
- The **when** expression can contain only global-object variables; parameter or local variables are disallowed ⇒ no direct dating-service.
- Eliminate restrictions and dating service is solvable.

```
_Monitor DatingService {
    AUTOMATIC_SIGNAL;
    int girls[noOfCodes], boys[noOfCodes]; // count girls/boys waiting
    bool exchange;                         // performing phone-number exchange
    int girlPhoneNo, boyPhoneNo;           // communication variables
  public:
    int girl( int phoneNo, int ccode ) {
        girls[ccode] += 1;
        if ( boys[ccode] == 0 ) {          // no boy waiting ?
            WAITUNTIL( boys[ccode] != 0, , ); // use parameter, not at start
            boys[ccode] -= 1;              // decrement dating pair
            girls[ccode] -= 1;
            girlPhoneNo = phoneNo;         // girl's phone number for exchange
            exchange = false;              // wake boy
        } else {
            girlPhoneNo = phoneNo;         // girl's phone number before exchange
            exchange = true;               // start exchange
            WAITUNTIL( ! exchange, , ); // wait until exchange complete, not at start
        }
        EXIT();
        return boyPhoneNo;
    }
    // boy
};
```

- E.g., task bounded-buffer:

```
task type buffer is  -- _Task
  . . . -- buffer declarations
  count : integer := 0;
begin -- thread starts here (task main)
  loop
    select  -- _Accept
      when count < Size =>  -- guard
      accept insert(elem : in ElemType) do -- mutex member
        -- add to buffer
        count := count + 1;
      end;
      -- executed if this accept called
    or
      when count > 0 =>  -- guard
      accept remove(elem : out ElemType) do -- mutex member
        -- remove from buffer, return via parameter
        count := count - 1;
      end;
    end select;
  end loop;
end buffer;
var b : buffer      -- create a task
```

- **select** is external scheduling and only appears in **task** main.
- Hence, Ada has no direct internal-scheduling mechanism, i.e., no condition variables.
- Instead a **requeue** statement can be used to make a ***blocking*** call to another (usually non-public) mutex member of the object.
- The original call is re-blocked on that mutex member's entry queue, which can be subsequently accepted when it is approriate to restart it.
- However, all **requeue** techniques suffer the problem of dealing with accumulated temporary results:
  - If a call must be postponed, its temporary results must be returned and bundled with the initial parameters before forwarding to the mutex member handling the next step,
  - or the temporary results must be re-computed at the next step (if possible).
- In contrast, waiting on a condition variable automatically saves the execution location and any partially computed state.

11.4.2 SR/Concurrent C++

- SR and Concurrent C++ have tasks with external scheduling using an accept statement.
- But no condition variables or requeue statement.

- To ameliorate lack of internal scheduling add a **when** and by clause on the **accept** statement.

- **when** clause is allowed to reference caller's arguments via parameters of mutex member:

```
select
    accept mem( code : in Integer )
        when code % 2 = 0 do ...    -- accept call with even code
or
    accept mem( code : in Integer )
        when code % 2 = 1 do ...    -- accept call with odd code
end select;
```

- **when** placed after the **accept** clause so parameter names are defined.

- **when** referencing parameter ⇒ implicit search of waiting tasks on mutex queue ⇒ locking mutex queue.

- Select longest waiting if multiple true **when** clauses.

- **by** clause is calculated for each true **when** clause and the minimum **by** clause is selected.

```
select
    accept mem( code : in Integer )
        when code % 2 = 0 by -code do ...-- accept largest even code
or
    accept mem( code : in Integer )
        when code % 2 = 1 by code do ...-- accept smallest odd code
end select;
```

- Select longest waiting if multiple by clauses with same minimum.

- **by** clause exacerbates the execution cost of computing **accept** clause.

- While **when/by** removes some internal scheduling and/or requeues, constructing expressions can be complex.

- Still situations that cannot be handled, e.g., if selection criteria involves multiple parameters:

  - select lowest even value of code1 and highest odd value of code2 if there are multiple lowest even values.

  - selection criteria involves information from other mutex queues such as the dating service (girl must search the boy mutex queue).

- Often simplest to unconditionally accept a call allowing arbitrarily examination, and possibly postpone (internal scheduling).

11.4.3 Java

- Java's concurrency constructs are largely derived from Modula-3.

```
class Thread implements Runnable {
    public Thread();
    public Thread(String name);
    public String getName();
    public void setName(String name);
    public void run(); // uC++ main
    public synchronized void start();
    public static Thread currentThread();
    public static void yield();
    public final void join();
}
```

- Thread is like μC++ uBaseTask, and all tasks must explicitly inherit from it:

```
class MyTask extends Thread {   // inheritance
    private int arg;            // communication variables
    private int result;
    public MyTask() {...}       // task constructors
    public void run() {...}     // task main
    public int result() {...}   // return result
    // unusual to have more members
}
```

- Thread starts in member run.
- Java requires explicit starting of a thread by calling start after the thread's declaration.

  ⇒ coding convention to start thread or inheritance is precluded (can only start a thread once)
- Termination synchronization is accomplished by calling join.
- Returning a result on thread termination is accomplished by member(s) returning values from the task's global variables.

```
mytask th = new MyTask(...);    // create and initialized task
th.start();                     // start thread
// concurrency
th.join();                      // wait for thread termination
a2 = th.result();               // retrieve answer from task object
```

- Like μC++, when the task's thread terminates, it becomes an object, hence allowing the call to result to retrieve a result.
- (see Section 8.11, p. 161 for monitors)
- While it is possible to have public **synchronized** members of a task:
  - no mechanism to manage direct calls, i.e., no accept statement

- ◦ ⇒ complex emulation of external scheduling with internal scheduling for direct communication

11.4.4 Go

- Non-object-oriented, light-weight (like μC++) ***non-preemptive*** threads (called **goroutine**).
  - cooperative scheduling: implicitly inserts yields at safe points (not interrupt based).
  - ⇒ busy waiting only on multicore (Why?)
- **go** statement (like start/fork) creates new user thread running in routine.

```
go foo( 3, f )    // start thread in routine foo
```

- Arguments may be passed to goroutine but return value is discarded.
- **Cannot reference goroutine object** ⇒ no direct communication.
- All threads terminate silently when program terminates.
- Threads synchronize/communicate via **channel** (CSP)
  - ⇒ **paradigm shift from routine call**.
- Channel is a typed shared buffer with 0 to N elements.

```
ch1 := make( chan int, 100 )       // integer channel with buffer size 100
ch2 := make( chan string )         // string channel with buffer size 0
ch2 := make( chan chan string )    // channel of channel of strings
```

- Buffer size > 0 ⇒ up to N asynchronous calls; otherwise, synchronous call.
- Operator **<–** performs send/receive.
  - send: `ch1 <– 1`
  - receive: `s <– ch2`
- Channel can be constrained to only send or receive; otherwise bi-directional.
- More like futures and _Select, and asynchronous call.

```
package main
import "fmt"
func main() {

    type Msg struct{ i, j int }
    ch1 := make( chan int )
    ch2 := make( chan float32 )
    ch3 := make( chan Msg )
    hand := make( chan string )
    shake := make( chan string )
    gortn := func() {
        var i int;  var f float32;  var m Msg
        L: for {
            select { // wait for message
              case i = <- ch1: fmt.Println( i )
              case f = <- ch2: fmt.Println( f )
              case m = <- ch3: fmt.Println( m )

              case <- hand: break L // sentinel
            }
        }
        shake <- "SHAKE" // completion
    }

    go gortn()        // start thread in gortn
    ch1 <- 0          // different messages
    ch2 <- 2.5
    ch3 <- Msg{1, 2}
    hand <- "HAND" // sentinel value
    <-shake           // wait for completion
}
```

```
#include <iostream>
using namespace std;
_Task Gortn {
  public:
    struct Msg { int i, j; };
    void mem1( int i ) { Gortn::i = i; }
    void mem2( float f ) { Gortn::f = f; }
    void mem3( Msg m ) { Gortn::m = m; }
  private:
    int i;  float f;  Msg m;
    void main() {

        L: for ( ;; ) {

            _Accept( mem1 ) cout << i << endl;
            or _Accept( mem2 ) cout << f << endl;
            or _Accept( mem3 ) cout << "{" << m.i
                 << " " << m.j << "}" << endl;
            or_Accept( ~Gortn ) break L;
        }
    }

};
int main() {
    Gortn gortn;
    gortn.mem1( 0 );
    gortn.mem2( 2.5 );
    gortn.mem3( (Gortn::Msg){ 1, 2 } );

} // wait for completion
```

- Locks

```
type Mutex                  // mutual exclusion lock
    func (m *Mutex) Lock()
    func (m *Mutex) Unlock()
type Cond                   // synchronization lock
    func NewCond(l Locker) *Cond
    func (c *Cond) Broadcast()
    func (c *Cond) Signal()
    func (c *Cond) Wait()
type Once                   // singleton-pattern
    func (o *Once) Do(f func())

type RWMutex                // readers/writer lock
    func (rw *RWMutex) Lock()
    func (rw *RWMutex) RLock()
    func (rw *RWMutex) RLocker() Locker
    func (rw *RWMutex) RUnlock()
    func (rw *RWMutex) Unlock()

type WaitGroup              // countdown lock
    func (wg *WaitGroup) Add(delta int)
    func (wg *WaitGroup) Done()
    func (wg *WaitGroup) Wait()
```

- Atomic operations

```
func AddInt32(val *int32, delta int32) (new int32)
func AddInt64(val *int64, delta int64) (new int64)
func AddUint32(val *uint32, delta uint32) (new uint32)
func AddUint64(val *uint64, delta uint64) (new uint64)
func AddUintptr(val *uintptr, delta uintptr) (new uintptr)
func CompareAndSwapInt32(val *int32, old, new int32) (swapped bool)
func CompareAndSwapInt64(val *int64, old, new int64) (swapped bool)
func CompareAndSwapPointer(val *unsafe.Pointer, old, new unsafe.Pointer) (swapped bool)
func CompareAndSwapUint32(val *uint32, old, new uint32) (swapped bool)
func CompareAndSwapUint64(val *uint64, old, new uint64) (swapped bool)
func CompareAndSwapUintptr(val *uintptr, old, new uintptr) (swapped bool)
func LoadInt32(addr *int32) (val int32)
func LoadInt64(addr *int64) (val int64)
func LoadPointer(addr *unsafe.Pointer) (val unsafe.Pointer)
func LoadUint32(addr *uint32) (val uint32)
func LoadUint64(addr *uint64) (val uint64)
func LoadUintptr(addr *uintptr) (val uintptr)
func StoreInt32(addr *int32, val int32)
func StoreInt64(addr *int64, val int64)
func StorePointer(addr *unsafe.Pointer, val unsafe.Pointer)
func StoreUint32(addr *uint32, val uint32)
func StoreUint64(addr *uint64, val uint64)
func StoreUintptr(addr *uintptr, val uintptr)
```

11.4.5 C++11 Concurrency

- C++11 library can be sound as C++ now has strong memory-model (SC).
- compile: `g++ -std=c++11 -pthread ...`
- Thread creation: start/wait (fork/join) approach.

```
class thread {
  public:
    template <class Fn, class... Args>
         explicit thread( Fn && fn, Args &&... args );
    void join();                        // termination synchronization
    bool joinable() const;              // true => joined, false otherwise
    void detach();                      // independent lifetime
    id get_id() const;                  // thread id
};
```

- Passing multiple arguments uses C++11's variadic template feature to provide a type-safe call chain via thread constructor to the *callable* routine.
- Any entity that is *callable* (functor) may be started:

```
#include <thread>
void hello( const string & s ) {          // callable
     cout << "Hello " << s << endl;
}
class Hello {                             // functor
     int result;
  public:
     void operator()( const string & s ) { // callable
          cout << "Hello " << s << endl;
     }
};

int main() {
     thread t1( hello, "Peter" );         // start thread in routine "hello"
     Hello h;                             // thread object
     thread t2( h, "Mary" );              // start thread in functor "h"
     // work concurrently
     t1.join();                           // termination synchronization
     // work concurrently
     t2.join();                           // termination synchronization
} // must join before closing block
```

- Thread starts implicitly at point of declaration.
- Instead of join, thread can run independently by detaching:

```
t1.detach();       // "t1" must terminate for program to end
```

- Beware dangling pointers to local variables:

```
{
     string s( "Fred" );                  // local variable
     thread t( hello, s );
     t.detach();
} // "s" deallocated and "t" running with reference to "s"
```

- **It is an error to deallocate thread object before join or detach.**
- Locks
  - mutex, recursive, timed, recursive-timed

```
class mutex {
  public:
     void lock();                   // acquire lock
     void unlock();                 // release lock
     bool try_lock();               // nonblocking acquire
};
```

◦ condition

```
class condition_variable {
  public:
    void notify_one();            // unblock one
    void notify_all();            // unblock all
    void wait( mutex &lock );     // atomically block & release lock
};
```

- Scheduling is no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck conditions.

```
#include <mutex>
class BoundedBuffer {                  // simulate monitor
    // buffer declarations
    mutex mlock;                       // monitor lock
    condition_variable empty, full;
    void insert( int elem ) {
        mlock.lock();
        while (count == Size ) empty.wait( mlock );  // release lock
        // add to buffer
        count += 1;
        full.notify_one();
        mlock.unlock();
    }

    int remove() {
        mlock.lock();
        while( count == 0 ) full.wait( mlock );  // release lock
        // remove from buffer
        count -= 1;
        empty.notify_one();
        mlock.unlock();
        return elem;
    }
};
```

- Futures

```
#include <future>
big_num pi( int decimal_places ) {...}
int main() {
    future<big_num> PI = async( pi, 1200 );  // PI to 1200 decimal places
    // work concurrently
    cout << "PI " << PI.get() << endl;       // block for answer
}
```

- Atomic types/operations

atomic_flag, atomic_bool, atomic_char, atomic_schar, atomic_uchar, atomic_short, atomic_ushort, atomic_int, atomic_uint, atomic_long, atomic_ulong, atomic_llong, atomic_ullong, atomic_wchar_t, atomic_address, atomic<T>

```
typedef struct atomic_itype {
    bool operator=(int-type) volatile;
    void store(int-type) volatile;
    int-type load() const volatile;
    int-type exchange(int-type) volatile;
    bool compare_exchange(int-type &old_value, int-type new_value) volatile;
    int-type fetch_add(int-type) volatile;
    int-type fetch_sub(int-type) volatile;
    int-type fetch_and(int-type) volatile;
    int-type fetch_or(int-type) volatile;
    int-type fetch_xor(int-type) volatile;

    int-type operator++() volatile;
    int-type operator++(int) volatile;
    int-type operator--() volatile;
    int-type operator--(int) volatile;
    int-type operator+=(int-type) volatile;
    int-type operator-=(int-type) volatile;
    int-type operator&=(int-type) volatile;
    int-type operator|=(int-type) volatile;
    int-type operator^=(int-type) volatile;
} atomic_itype;
```

11.5 Threads & Locks Library

11.5.1 java.util.concurrent

- Java library is sound because of memory-model and language is concurrent aware.
- Synchronizers : Semaphore (counting), CountDownLatch, CyclicBarrier, Exchanger, Condition, Lock, ReadWriteLock
- Use new locks to build a monitor with multiple condition variables.

```
class BoundedBuffer {                                   // simulate monitor
    // buffer declarations
    final Lock mlock = new ReentrantLock();      // monitor lock
    final Condition empty = mlock.newCondition();
    final Condition full = mlock.newCondition();
    public void insert( Object elem ) throws InterruptedException {
        mlock.lock();
        try {
            while (count == Size ) empty.await();   // release lock
            // add to buffer
            count += 1;
            full.signal();
        } finally { mlock.unlock(); } // ensure monitor lock is unlocked
    }
```

```
        public Object remove() throws InterruptedException {
            mlock.lock();
            try {
                while( count == 0 ) full.await();  // release lock
                // remove from buffer
                count -= 1;
                empty.signal();
                return elem;
            } finally { mlock.unlock(); } // ensure monitor lock is unlocked
        }
    }
```

- Condition is nested class within ReentrantLock ⇒ condition implicitly knows its associated (monitor) lock.
- Scheduling is still no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck condition.
- No connection with implicit condition variable of an object.
- **Do not mix implicit and explicit condition variables.**

• Executor/Future : (actor like)

- Executor is a server with one or more worker tasks (worker pool).
- Future is closure with work for executor (Callable) and place for result.
- Call to executor submit is asynchronous and returns a future.
- Result is retrieved using get routine, which may block until result inserted by executor.

```
import java.util.ArrayList;
import java.util.List;
import java.util.concurrent.*;
public class Matrix {
    public static void main( String[] args )
            throws InterruptedException, ExecutionException {
        class Adder implements Callable<Integer> {
            int row[ ], cols;                    // communication
            public Integer call() {
                int subtotal = 0;
                for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
                return subtotal;
            }
            Adder( int [ ] r, int c ) { row = r; cols = c; }
        }
```

```
        int rows = 10, cols = 10;
        int matrix[][] = new int[rows][cols], total = 0;
        // read matrix
        ExecutorService executor = Executors.newFixedThreadPool( 4 );
        List<Future<Integer>> subtotals = new ArrayList<Future<Integer>>();
        for ( int r = 0; r < rows; r += 1 )          // send off work for executor
            subtotals.add( executor.submit( new Adder( matrix[r], cols ) ) );
        for ( int r = 0; r < rows; r += 1 )          // wait for results
            total += subtotals.get( r ).get();        // retrieve result
        System.out.println( total );
        executor.shutdown();
    }
}
```

- μC++ also has fixed thread-pool executor (used with actors).

```
struct Adder {                                    // routine, functor or lambda
    int * row, cols;                              // communication
    int operator()() {                            // functor operator
        int subtotal = 0;
        for ( int c = 0; c < cols; c += 1 ) subtotal += row[c];
        return subtotal;
    }
    Adder( int row[ ], int cols ) : row( row ), cols( cols ) {}
};

int main() {
    const int rows = 10, cols = 10;
    int matrix[rows][cols], total = 0;
    // read matrix
    uExecutor executor( 4 );                      // kernel threads
    Future_ISM<int> subtotals[rows];
    Adder * adders[rows];
    for ( int r = 0; r < rows; r += 1 ) {         // send off work for executor
        adders[r] = new Adder( matrix[r], cols );
        subtotals[r] = executor.sendrecv( *adders[r] );
    }
    for ( int r = 0; r < rows; r += 1 ) {         // wait for results
        total += subtotals[r]();
        delete adders[r];
    }
    cout << total << endl;
}
```

- Collections : LinkedBlockingQueue, ArrayBlockingQueue, SynchronousQueue, PriorityBlockingQueue, DelayQueue, ConcurrentHashMap, ConcurrentSkipListMap, ConcurrentSkipListSet, CopyOnWriteArrayList, CopyOnWriteArraySet.
    - Create threads that interact indirectly through atomic data structures, e.g., producer/-consumer interact via LinkedBlockingQueue.

- Atomic Types using compare-and-set (see Section 11.1.1, p. 197) (i.e., lock-free).

  AtomicBoolean, AtomicInteger, AtomicIntegerArray, AtomicLong, AtomicLongArray, AtomicReference<V>, AtomicReferenceArray<E>

```
int v;
AtomicInteger i = new AtomicInteger();
i.set( 1 );
System.out.println( i.get() );
v = i.addAndGet( 1 );          // i += delta
System.out.println( i.get() + " " + v );
v = i.decrementAndGet();       // –i
System.out.println( i.get() + " " + v );
v = i.getAndAdd( 1 );          // i =+ delta
System.out.println( i.get() + " " + v );
v = i.getAndDecrement();       // i–
System.out.println( i.get() + " " + v );
```

```
1
2 2
1 1
2 1
1 2
```

11.5.2 Pthreads

- Several libraries exist for C (pthreads) and C++ (μC++).

- C libraries built around routine abstraction and mutex/condition locks ("attribute" parameters not shown).

```
int pthread_create( pthread_t * new_thread_ID,
        void * (*start_func)(void *), void * arg );
int pthread_join( pthread_t target_thread, void ** status );
pthread_t pthread_self( void );
int pthread_yield(void);

int pthread_mutex_init( pthread_mutex_t * mp );
int pthread_mutex_lock( pthread_mutex_t * mp );
int pthread_mutex_unlock( pthread_mutex_t * mp );
int pthread_mutex_destroy( pthread_mutex_t * mp );

int pthread_cond_init( pthread_cond_t * cp );
int pthread_cond_wait( pthread_cond_t * cp, pthread_mutex_t * mutex );
int pthread_cond_signal( pthread_cond_t * cp );
int pthread_cond_broadcast( pthread_cond_t * cp );
int pthread_cond_destroy( pthread_cond_t * cp );
```

- Thread starts in routine start_func via pthread_create.

  Initialization data is single **void** * value.

- Termination synchronization is performed by calling pthread_join.

- Return a result on thread termination by passing back a single **void** * value from pthread_join.

```
void * rtn( void * arg ) { . . . }
int i = 3, r, rc;
pthread_t t;                              // thread id
rc = pthread_create( &t, rtn, (void *)i ); // create and initialized task
if ( rc != 0 ) . . .                      // check for error
// concurrency
rc = pthread_join( t, &r );               // wait for thread termination and result
if ( rc != 0 ) . . .                      // check for error
```

- All C library approaches have type-unsafe communication with tasks.
- No external scheduling ⇒ complex direct-communication emulation.
- Internal scheduling is no-priority nonblocking ⇒ barging ⇒ wait statements must be in while loops to recheck conditions

```
typedef struct {                        // simulate monitor
    // buffer declarations
    pthread_mutex_t mutex;              // mutual exclusion
    pthread_cond_t full, empty;         // synchronization
} buffer;

// write your own constructor/destructor
void ctor( buffer * buf ) {             // constructor
    . . .
    pthread_mutex_init( &buf->mutex );
    pthread_cond_init( &buf->full );
    pthread_cond_init( &buf->empty );
}

void dtor( buffer * buf ) {             // destructor
    pthread_mutex_lock( &buf->mutex ); // must be mutex
    . . .
    pthread_cond_destroy( &buf->empty );
    pthread_cond_destroy( &buf->full );
    pthread_mutex_destroy( &buf->mutex );
}

void insert( buffer * buf, int elem ) {
    pthread_mutex_lock( &buf->mutex );
    while ( buf->count == Size )
        pthread_cond_wait( &buf->empty, &buf->mutex );
    // add to buffer
    buf->count += 1;
    pthread_cond_signal( &buf->full );
    pthread_mutex_unlock( &buf->mutex );
}
```

```
int remove( buffer * buf ) {
    pthread_mutex_lock( &buf->mutex );
    while ( buf->count == 0 )
        pthread_cond_wait( &buf->full, &buf->mutex );
    // remove from buffer
    buf->count -= 1;
    pthread_cond_signal( &buf->empty );
    pthread_mutex_unlock( &buf->mutex );
    return elem;
}
```

- Since there are no constructors/destructors in C, explicit calls are necessary to ctor/dtor before/after use.
- All locks must be initialized and finalized.
- Mutual exclusion must be explicitly defined where needed.
- Condition locks should only be accessed with mutual exclusion.
- pthread_cond_wait atomically blocks thread and releases mutex lock, which is necessary to close race condition on baton passing.

11.6 OpenMP

- Shared memory, implicit thread management (programmer hints), 1-to-1 threading model (kernel threads), some explicit locking.
- Communicate with compiler with #pragma directives.

```
#pragma omp ...
```

- fork/join model
  - fork: initial thread creates a team of parallel threads (including itself)
  - each thread executes the statements in the region construct
  - join: when team threads complete, synchronize and terminate, except initial thread which continues
- compile: gcc -std=c99 -fopenmp openmp.c -lgomp
- COBEGIN/COEND: each thread executes different section:

```
#include <omp.h>
. . . // declarations of p1, p2, p3
int main() {
    int i;
    #pragma omp parallel sections num_threads( 4 ) // fork "4" threads
    { // COBEGIN
        #pragma omp section
        { i = 1; }                  // BEGIN . . . END
        #pragma omp section
        { p1( 5 ); }
        #pragma omp section
        { p2( 7 ); }
        #pragma omp section
        { p3( 9 ); }
    } // COEND (synchronize)
}
```

- **for** directive specifies each loop iteration is executed by a team of threads (COFOR)

```
int main() {
    const unsigned int rows = 10, cols = 10;      // sequential
    int matrix[rows][cols], subtotals[rows], total = 0;
    // read matrix
    #pragma omp parallel for            // fork "rows" threads
    for ( unsigned int r = 0; r < rows; r += 1 ) {   // concurrent
        subtotals[r] = 0;
        for ( unsigned int c = 0; c < cols; c += 1 )
            subtotals[r] += matrix[r][c];
    }
    for ( unsigned int r = 0; r < rows; r += 1 )     // sequential
        total += subtotals[r];
    printf( "total:%d\n", total );
} // main
```

- In this case, sequential code directly converted to concurrent via #pragma.
- Variables outside section are shared; variables inside are thread private.
- Programmer responsible for sharing in vector/matrix manipulation.
- barrier

```
int main() {
    #pragma omp parallel num_threads( 4 ) // fork "4" threads
    {
        sleep( omp_get_thread_num() );
        printf( "%d\n", omp_get_thread_num() );
        #pragma omp barrier // wait for all block threads to arrive
        printf( "sync\n" );
    }
}
```

- Without omp section, all threads run same block (like omp parallel **for**).
- Barrier's trigger is the number of block threads.
- Threads sleeps for different times, but all print `"sync"` at same time.
- Also critical section and atomic directives.

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