Writing an Assembler: Part 1

MIPS Assembly Language

- Instead of writing machine language…

```
00000000010000010001100000100010
00000000000000000010000000010100
00000000000000000000000000000100
00000000011001000001100000100000
10001100000001010000000000000000
00000011111000000000000000001000
```

- It's easier to write (and read) assembly language!

```
sub $3, $2, $1   Subtract               ($3 = $2 - $1)
lis $4           Load Immediate & Skip  ($4 = MEM[PC]; PC += 4)
.word 4          Decimal Integer 4      (encoded as unsigned 32-bit word)
add $3, $3, $4   Add                    ($3 = $3 + $4)
lw $5, 0($0)     Load Word              ($5 = MEM[$0 + 0])
jr $31           Jump Register          (PC = $31)
```

MIPS Assembly Language

- We've learned six machine language instructions so far.
- Eleven remain to be discussed (in our dialect of MIPS).
- The syntax is similar to the ones we've already seen. For example:
  - mult $s, $t (multiplication)
  - div $s, $t (division)
  - slt $d, $s, $t (less-than comparison)
  - beq $s, $t, i (conditional branching)
- Before we get back into MIPS programming, let's learn how to actually translate this convenient syntax into machine language.

MIPS Syntax in Detail

- When discussing machine language, we learned there are two basic formats for instruction encoding:
  - **Register Format**: `000000 sssss ttttt ddddd 00000 ffffff`
    - The s, t and d bit sequences encode **register numbers** (0 to 31).
    - The first 6 bits, the **opcode bits**, are always zero in Register Format instructions.
    - When the opcode bits are zero, the MIPS machine looks at the **function bits**, the last 6 bits, to determine which instruction to execute.
  - **Immediate Format**: `oooooo sssss ttttt iiiiiiiiiiiiiiii`
    - The s and t bit sequences encode **register numbers** (0 to 31).
    - The i bits encode a 16-bit **immediate (constant) value**.
    - The first 6 bits, the **opcode bits**, are non-zero and indicate which instruction to perform.

MIPS Syntax in Detail

- **Register Format**: `000000 sssss ttttt ddddd 00000 ffffff`
  - 13 of our MIPS instructions use this format. The assembly syntax is:

```
add   $d, $s, $t
sub   $d, $s, $t
slt   $d, $s, $t
sltu  $d, $s, $t
```

Three Operands

```
mult      $s, $t
multu     $s, $t
div       $s, $t
divu      $s, $t
```

Two Operands

```
lis   $d
mflo  $d
mfhi  $d
```

One Operand ($d)

```
jr        $s
jalr      $s
```

One Operand ($s)

MIPS Syntax in Detail

- **Immediate Format**: `oooooo sssss ttttt iiiiiiiiiiiiiiii`
  - Four of our instructions use this format:

```
beq $s, $t, i
bne $s, $t, i
lw $t, i($s)
sw $t, i($s)
```

Branch instructions

Memory instructions

- What if we want to specify something that's not an instruction, like a constant to load with Load Immediate & Skip?

  .word i is used to encode the decimal or hexadecimal value i as a 32-bit word.
  - If i is a negative decimal number, two's complement encoding is used.
  - If i is a non-negative decimal number, unsigned encoding is used.
  - If i is hexadecimal, each hex digit is translated directly into a 4-bit chunk (nibble).

Assemblers

- An **assembler** is a program that translates assembly language into machine language.
- To translate a line of code like "add $1, $2, $3", the process might be:
  - Break down the line into meaningful chunks (with a scanner!)
  - Check that the syntax of the line makes sense.
  - Look up the function bits for "add" in a hardcoded lookup table.
  - Extract the numbers 1, 2 and 3 from the register tokens.
  - Use this data to "fill in" the register format encoding and output it.
- **Register Format**: `000000 sssss ttttt ddddd 00000 ffffff`

Structure of a MIPS Assembly Program

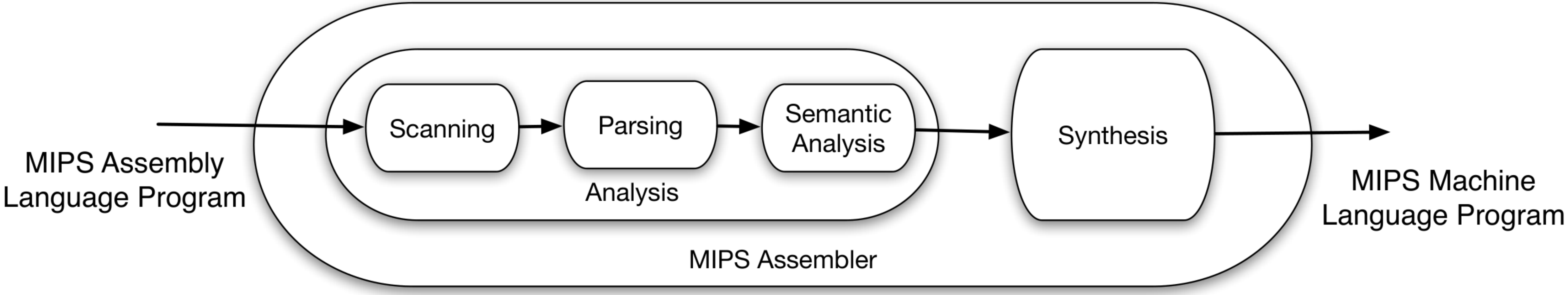
- A MIPS program is divided into lines.
- A line can have *at most* one instruction (or .word directive).
- Lines can also be blank, or consist only of a **comment**.
  - A semicolon ; starts a comment, which runs to the end of the line.
- There's also a feature we haven't talked about yet called **labels**.
  - Labels let you assign a name to a particular location in the program, so that you can refer to it later.
  - A line can start with any number of labels, but labels must appear before the instruction on a line.
  - You can also have label-only lines…

A Simplifying Assumption

- We'll ignore blank lines, comments, and labels and assume for now:

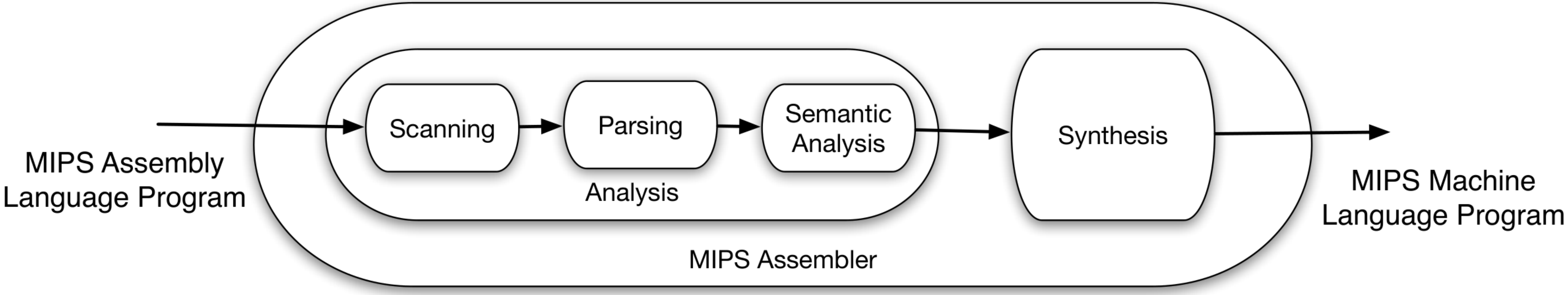
  Every line contains exactly one instruction or .word directive.
- This means that every line of MIPS assembly language translates into **exactly one 32-bit binary word**.
- This assumption is convenient for the assembler writer but not for the assembly programmer!
- We'll remove this assumption in the second version of our assembler.
  - Blank lines and comments are easy – just have the **scanner** ignore them.
  - Labels are **tricky** and will require significant refactoring.

The Phases of Assembly (and Compilation!)



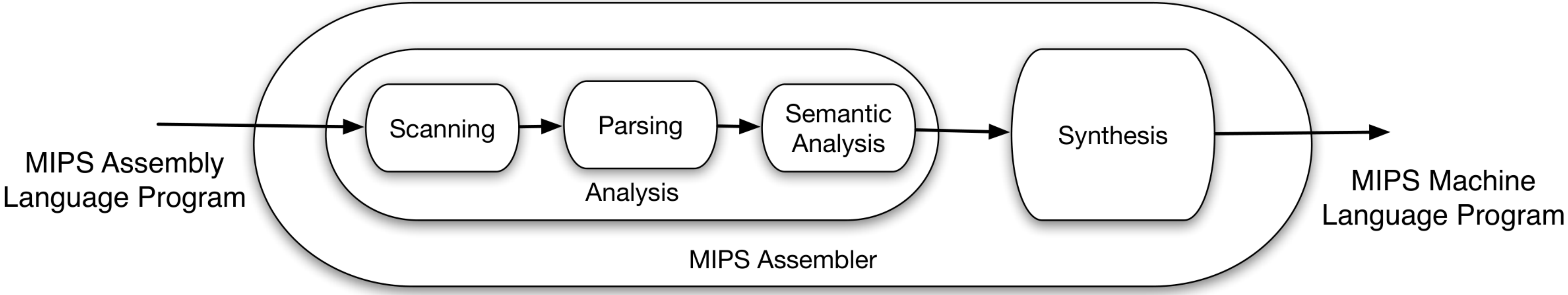
- The term *compiler* usually refers to a tool that translates a "high-level" language to a "low-level" language, but more generally, it can mean any tool that translates between two programming languages.
- An assembler can be viewed as a "low-level to lower-level" compiler.

The Phases of Assembly (and Compilation!)



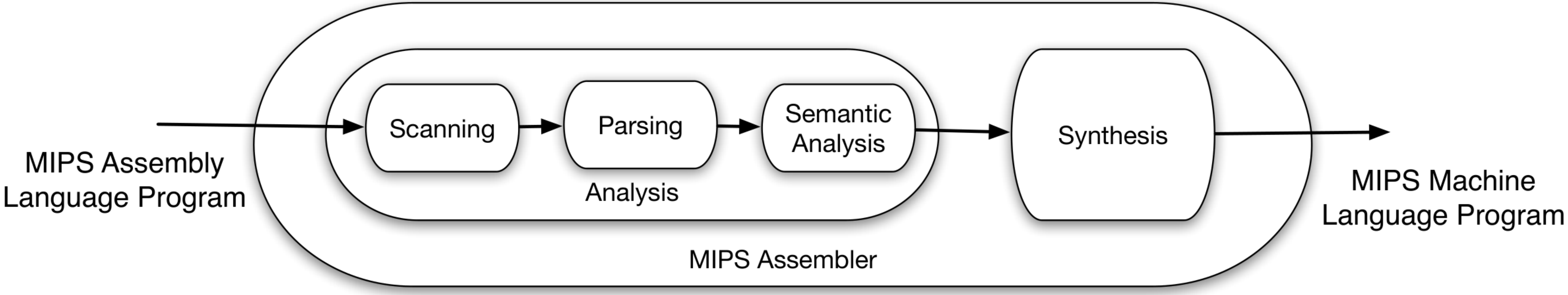
- The compilation process can be broadly divided into two phases:
  - **Analysis:** Understand the meaning of the source program.
  - **Synthesis:** Output an equivalent program in the target language.

The Phases of Assembly (and Compilation!)



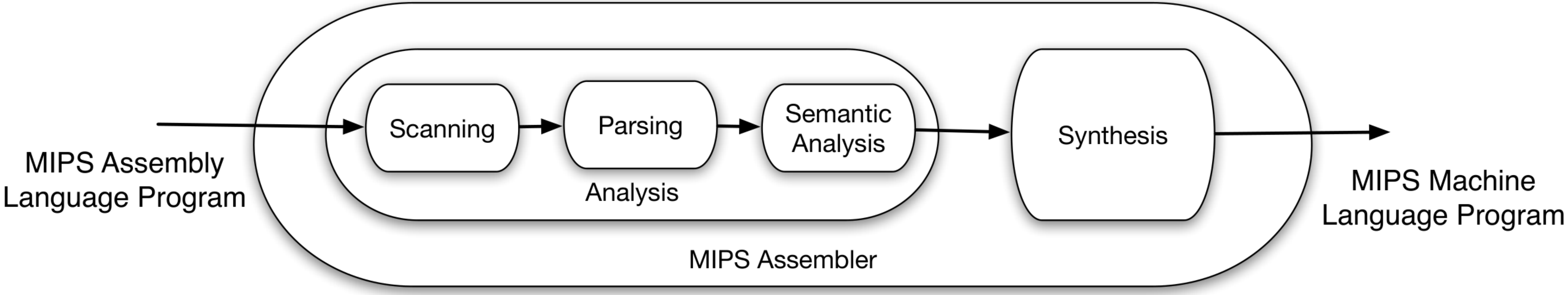
- **Analysis** is usually divided further into three steps:
  - **Scanning:** Analysis of lexemes (grouping characters into meaningful strings).
  - **Parsing:** Analysis of syntax (grouping strings into larger structures).
  - **Semantic Analysis:** Analysis of semantics (meaning of structures in context).

The Phases of Assembly (and Compilation!)



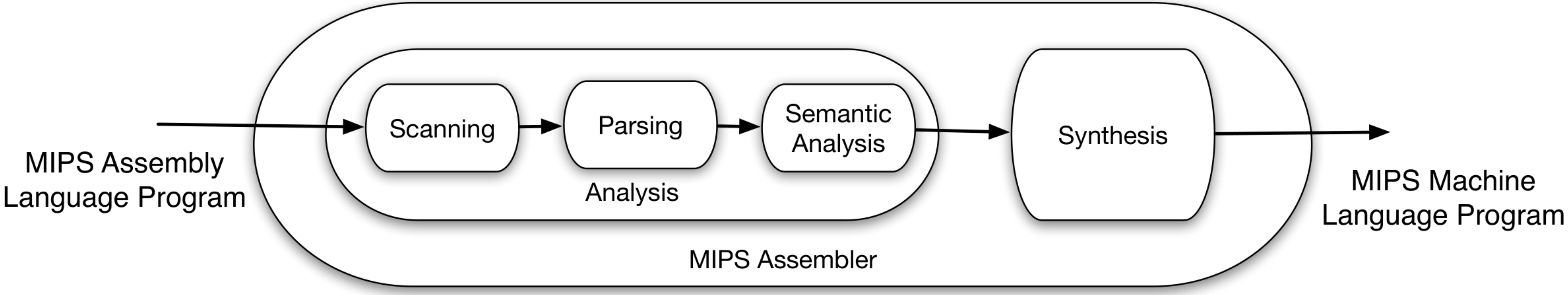
- **Parsing** in an assembler involves looking at the tokens and figuring out which groups of tokens constitute an **instruction** or **directive**, while rejecting groups of tokens that are nonsensical (syntax errors).

The Phases of Assembly (and Compilation!)



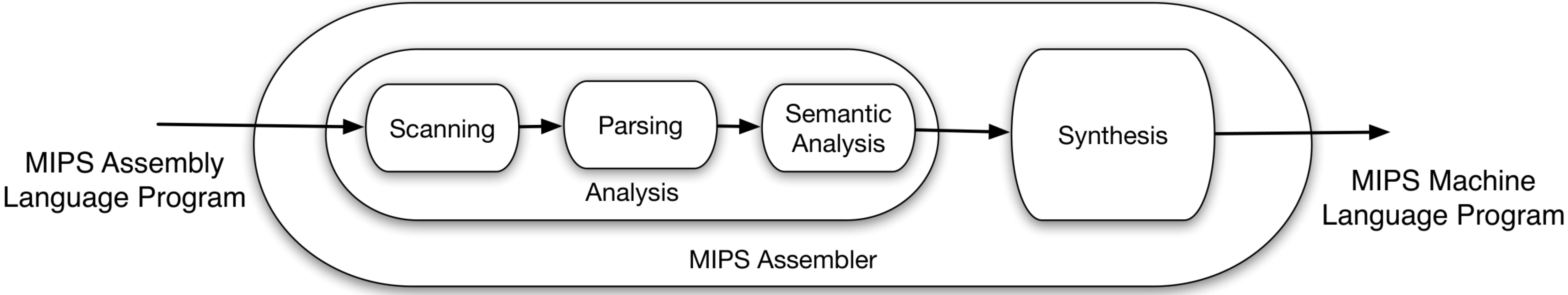
- In high-level languages, which usually have complex nesting as opposed to the simple line-based style of assembly, the parsing phase groups tokens together into a **tree** representing the structure and components of the program.

The Phases of Assembly (and Compilation!)



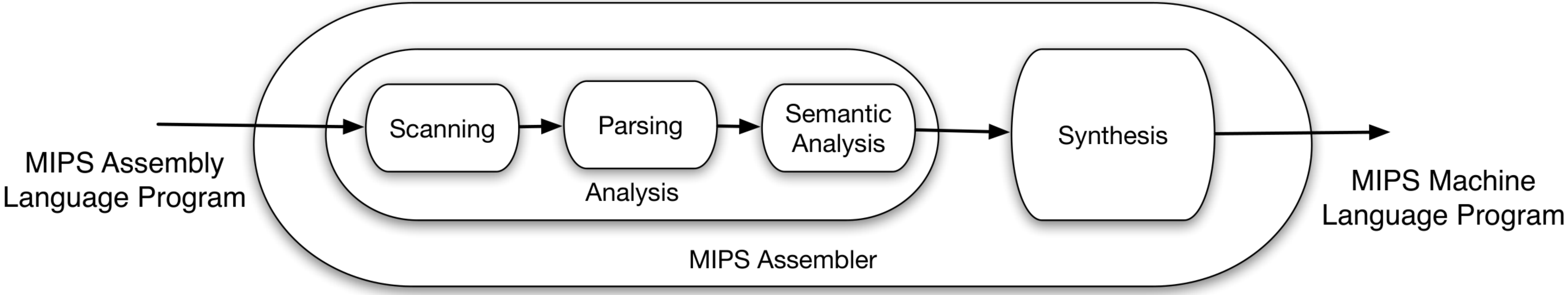
- There is little to be done for **semantic analysis** in an assembler. Each instruction can be translated without considering its meaning in the wider context of the program… at least until **labels** are introduced. (More on this later)

The Phases of Assembly (and Compilation!)



- In high-level languages, semantic analysis often deals with issues involving **identifier names** (variable, functions, etc.) and **types**. The C statement "int x = y;" is syntactically valid but the *meaning in context* might not make sense (maybe y is undefined, or y is a pointer).

The Phases of Assembly (and Compilation!)



- Once the structure of the source program is understood, the **Synthesis** phase produces an equivalent program in the target language. For an assembler, this means producing a machine language program equivalent to the assembly language program.

Scanning

- We've learned how to scan using maximal munch or simplified maximal munch. We just need a scanning DFA.
- Let's review the syntax again to figure out what tokens we need:
    - Instructions with register operands:

```
jr $31              add $1, $2, $3
```

    - The .word directive (accepts signed decimal and unsigned hex):

```
.word 241           .word -37           .word 0xCAFEBEEF
```

    - Instructions with immediate operands (signed decimal or unsigned hex):

```
beq $1, $2, -1      lw $31, -4($30)     sw $1, 0x14($0)
```

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- We've learned how to scan using maximal munch or simplified maximal munch. We just need a scanning DFA.
- Let's review the syntax again to figure out what tokens we need:
  - Instructions with register operands:

    `jr` `$31` **`add`** `$1, $2, $3`
  - The .word directive (accepts signed decimal and unsigned hex):

    `.word 241` `.word -37` `.word 0xCAFEBEEF`
  - Instructions with immediate operands (signed decimal or unsigned hex):

    `beq` `$1, $2, -1` **`lw`** `$31, -4($30)` **`sw`** `$1, 0x14($0)`
- Instruction identifiers

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  - Instructions with register operands:

    `jr $31` `add $1, $2, $3`
  - The .word directive (accepts signed decimal and unsigned hex):

    `.word` `241` **`.word`** `-37` **`.word`** `0xCAFEBEEF`
  - Instructions with immediate operands (signed decimal or unsigned hex):

    `beq $1, $2, -1` `lw $31, -4($30)` `sw $1, 0x14($0)`
- Directive identifiers (like instructions, but start with a dot)

Scanning

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  - Instructions with immediate operands (signed decimal or unsigned hex):

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- Registers

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- Let's review the syntax again to figure out what tokens we need:
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      jr $31              add $1, $2, $3
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    - The .word directive (accepts signed decimal and unsigned hex):

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    - Instructions with immediate operands (signed decimal or unsigned hex):

      ```
      beq $1, $2, -1      lw $31, -4($30)     sw $1, 0x14($0)
      ```

- Decimal immediates

Scanning

- We've learned how to scan using maximal munch or simplified maximal munch. We just need a scanning DFA.
- Let's review the syntax again to figure out what tokens we need:
    - Instructions with register operands:

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      jr $31               add $1, $2, $3
      ```

    - The .word directive (accepts signed decimal and unsigned hex):

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      .word 241            .word -37            .word 0xCAFEBEEF
      ```

    - Instructions with immediate operands (signed decimal or unsigned hex):

      ```
      beq $1, $2, -1       lw $31, -4($30)      sw $1, 0x14($0)
      ```

- Hexadecimal immediates

Scanning

- We've learned how to scan using maximal munch or simplified maximal munch. We just need a scanning DFA.
- Let's review the syntax again to figure out what tokens we need:
  - Instructions with register operands:

    `jr $31` `add $1, $2, $3`
  - The .word directive (accepts signed decimal and unsigned hex):

    `.word 241` `.word -37` `.word 0xCAFEBEEF`
  - Instructions with immediate operands (signed decimal or unsigned hex):

    `beq $1, $2, -1` `lw $31, -4($30)` `sw $1, 0x14($0)`
- Punctuation (commas, parentheses)

Scanning

- We've learned how to scan using maximal munch or simplified maximal munch. We just need a scanning DFA.
- Let's review the syntax again to figure out what tokens we need:
  - Instructions with register operands:

    ```
    jr $31                 add $1, $2, $3
    ```

  - The .word directive (accepts signed decimal and unsigned hex):

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    .word 241              .word -37              .word 0xCAFEBEEF
    ```

  - Instructions with immediate operands (signed decimal or unsigned hex):

    ```
    beq $1, $2, -1         lw $31, -4($30)        sw $1, 0x14($0)
    ```

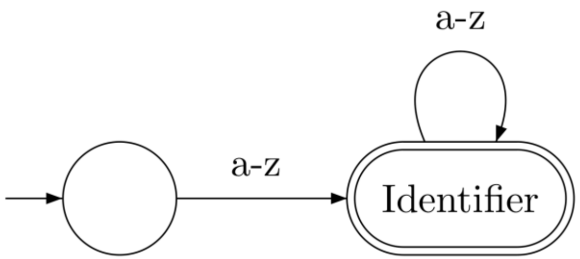
- We also need to deal with whitespace and newlines in the program…

Constructing the Scanning DFA

- We'll build DFAs for each of the following token kinds:
  - Instruction identifiers
  - Directive identifiers
  - Registers
  - Decimal immediates
  - Hexadecimal immediates
  - Punctuation
- We'll also discuss how to handle whitespace and newlines.
- Then we'll figure out how to combine everything into one large DFA!

Instruction Identifiers

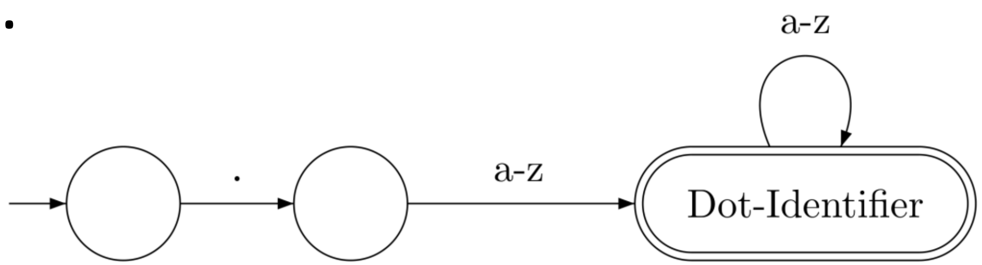
- We could have separate token kinds for each of the 17 instructions.
- But designing our DFA to recognize these specific 17 strings would be annoying. We will take a simpler approach:



- Any sequence of lowercase letters is an **Identifier** token.
- We'll expand the definition of an **Identifier** when we introduce **labels** later on. For now, this is good enough.

Directive Identifiers

- Right now, the only directive we have is **.word**, so we could just hardcode our DFA to recognize .word.
- We'll be more general and define a **Dot-Identifier** to be an **Identifier** with a dot in front.

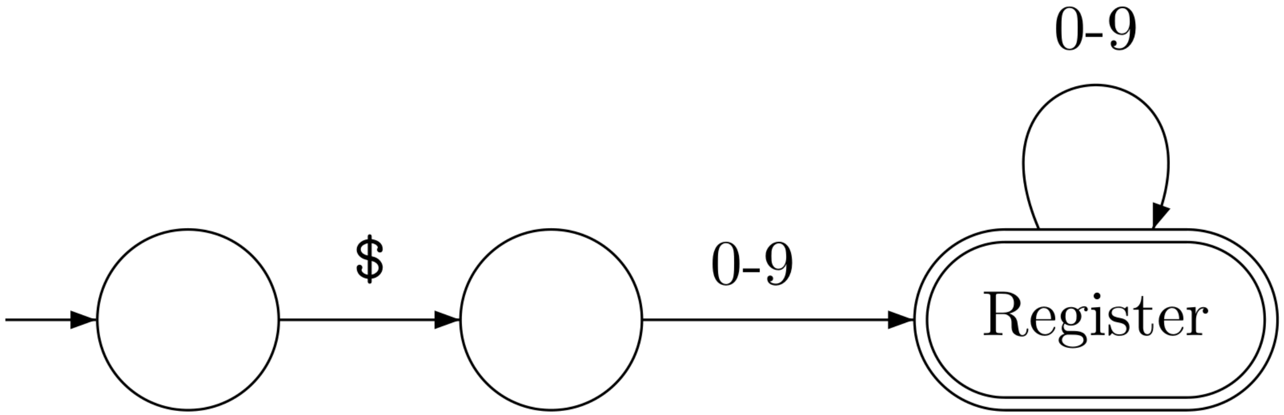


- We'll learn about two more directives later, but you won't be asked to implement them on assignments.

Registers

- Recognizing a $ sign followed by a sequence of digits is straightforward, but how strict do we want to be?
  - Should we accept things like $007 with useless leading zeroes?
  - Should we accept invalid register numbers like $32 or $241?
- Leading zeroes are probably okay but we want to treat invalid register numbers as an error.
- However, doing numeric range checking *in a DFA* can be awkward.
- Let's keep our DFA simple and do range checking *outside the DFA*.
- *After* producing a token, extract the number and check its range.

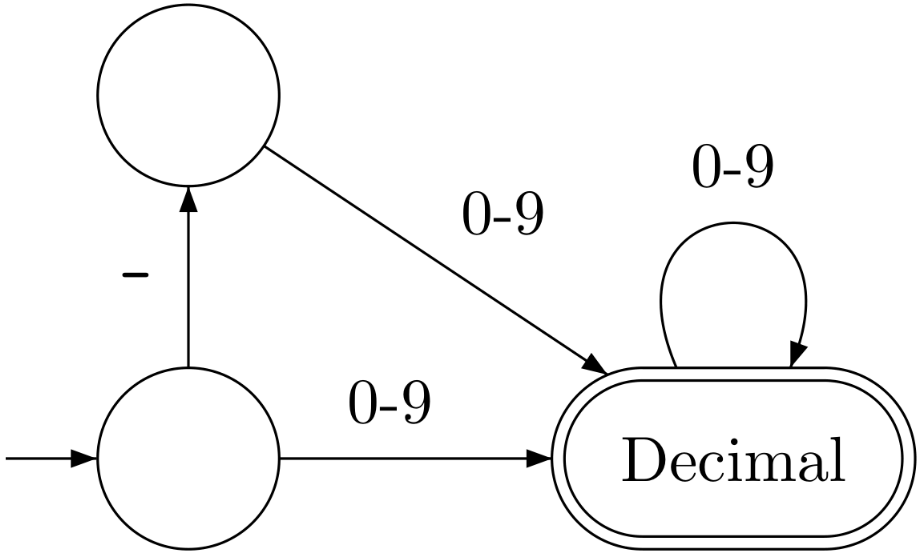
Registers



- This simple DFA treats things like $2147483648 as a valid **Register** token, but that's okay.
- Once simplified maximal munch finds a token, we can examine the token's lexeme and do a range check in our *high-level* code.

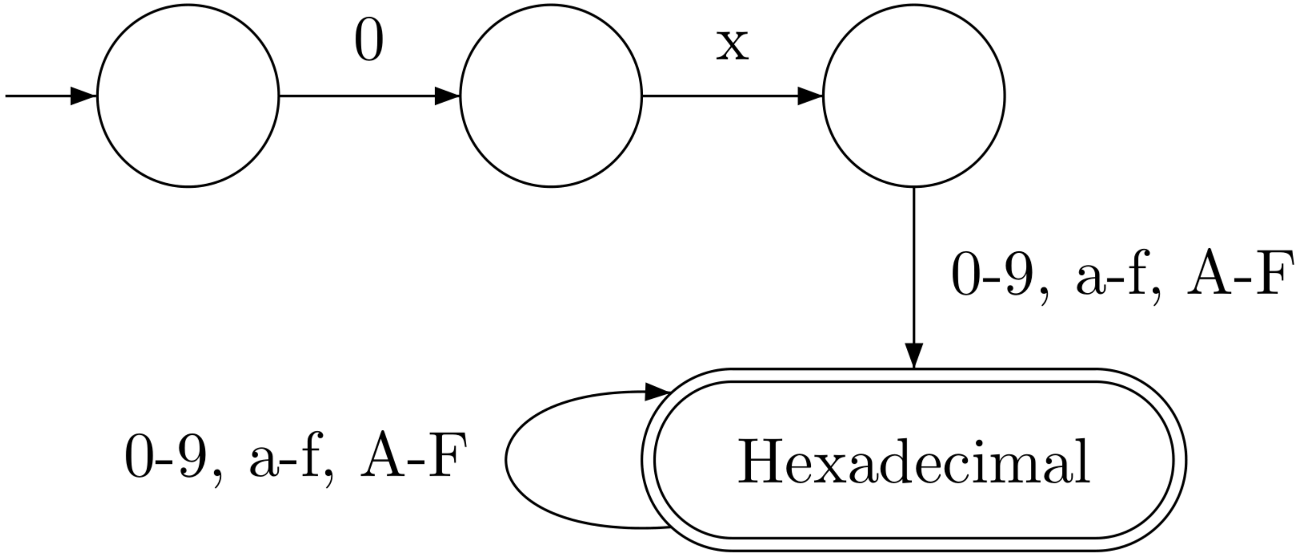
Decimal Immediates

- We are not strict here, and we allow things like useless leading zeroes and the strange sequence -0 in **Decimal** tokens.



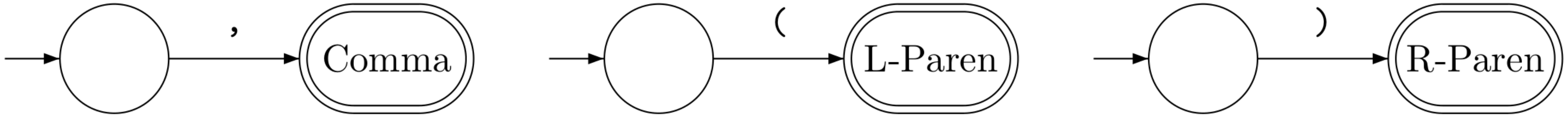
Hexadecimal Immediates

- Recognizing **Hexadecimal** tokens is straightforward on its own, but it will be a little tricky to combine this with the previous DFA.
- "0" could be a decimal number OR the start of "0x…"



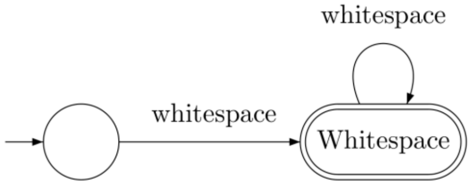
Punctuation

- We treat all three punctuation characters as separate token kinds because they are used in different syntactic contexts.



Handling Non-Newline Whitespace

- We want to filter out non-newline whitespace because it has no meaning in a MIPS program.
  - On the other hand, MIPS is a line-based language, so newlines are important.
- Two approaches:

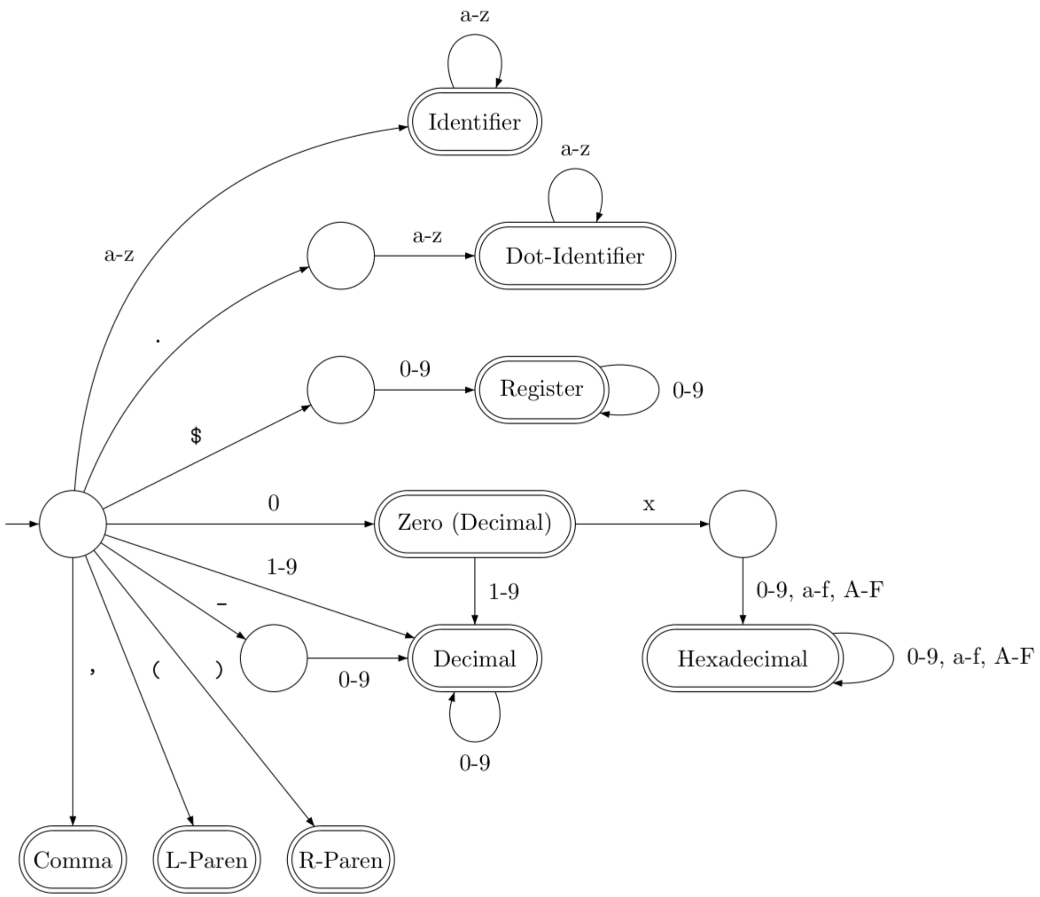


  - Create a token kind for **Whitespace**, but modify our scanner so that when it detects a **Whitespace** token, it simply discards it instead of adding it to the tokenization.
  - Augment (simplified) maximal munch with logic that skips past whitespace after producing a token before reading the next token. (No change to DFA)
- We'll use the second approach in these slides so our DFA is less complicated, but we'll use the first approach in the scanning project.

Handling Newlines

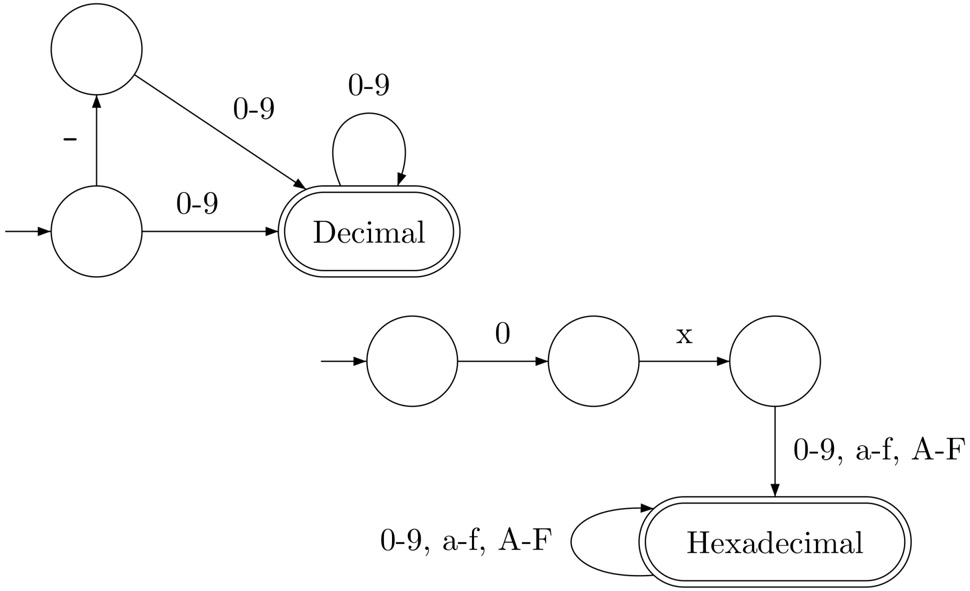
- Newlines can't just be discarded because they have actual meaning in a MIPS program (they separate instructions).
- We can approach this in two ways.
  - Modify the DFA to recognize newlines and output them as their own token.
  - Leave the DFA as is. Then, when writing the assembler, have it run the scanner *on each line individually* instead of on the entire program.
- Again, for these slides, we'll use the approach that doesn't involve making our DFA more complicated.
- For the project we will ask you to output **Newline** tokens.

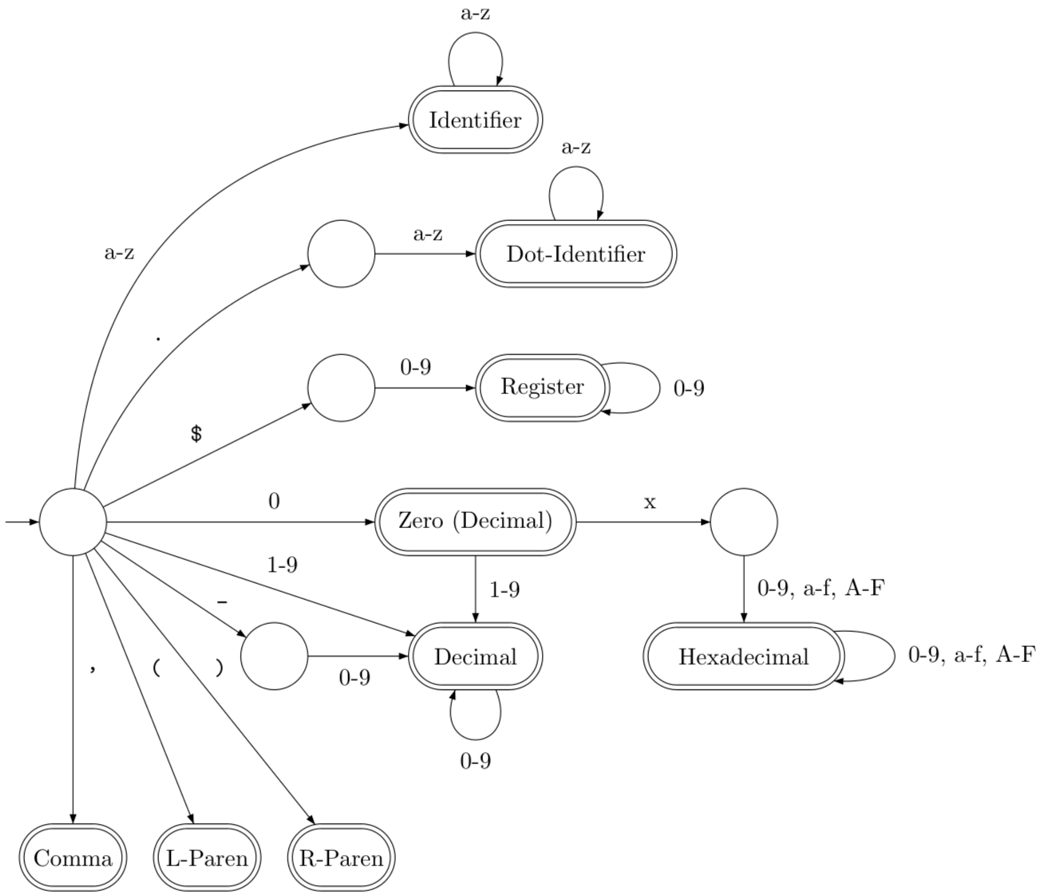
The Complete Scanning DFA



Decimal and Hexadecimal

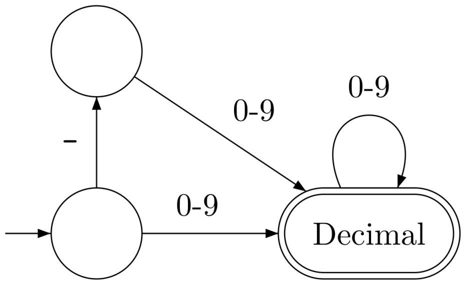
- The only tricky part of combining the DFAs is how we handled the **Decimal** and **Hexadecimal** tokens.

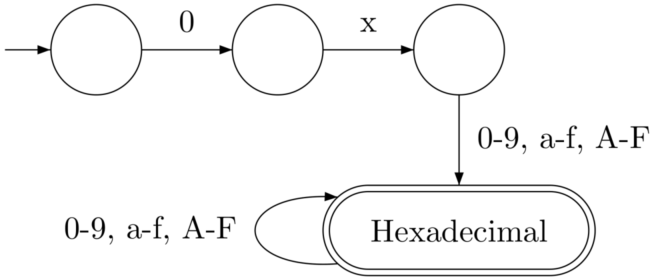


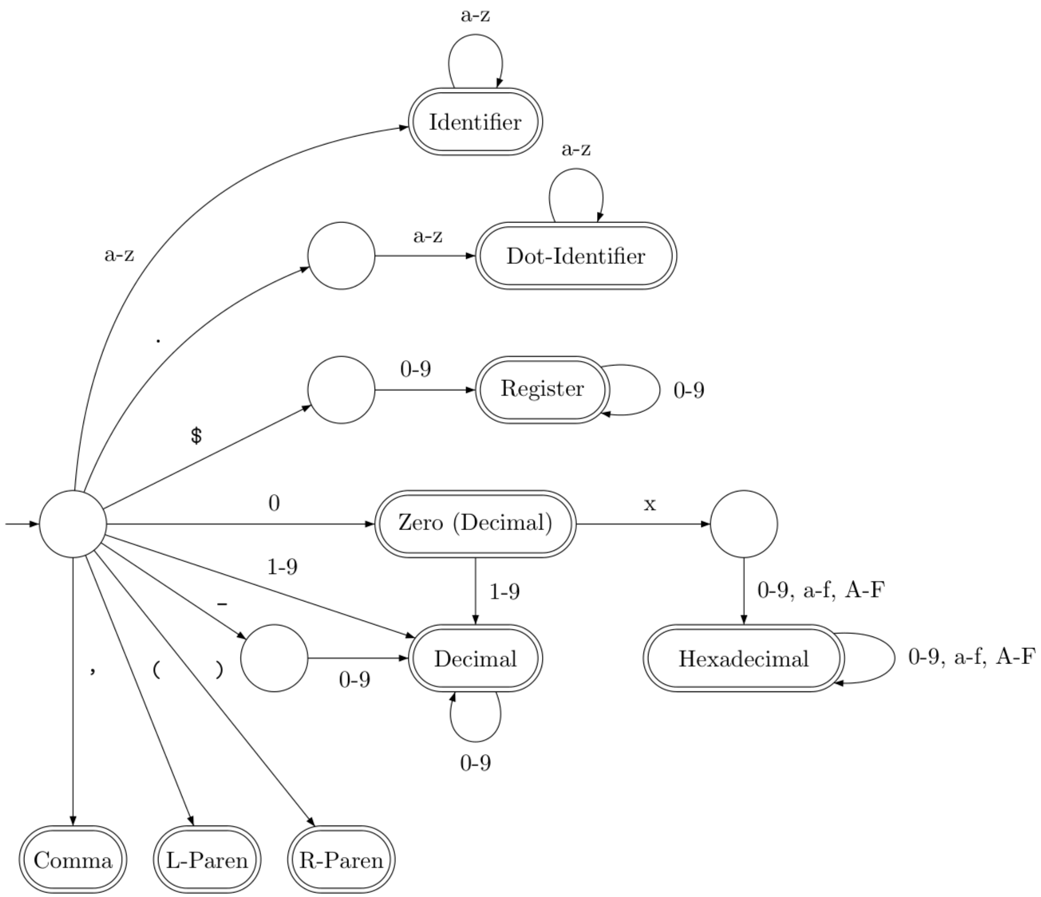


Decimal and Hexadecimal

- We created a separate state for the decimal number **Zero**. Why?

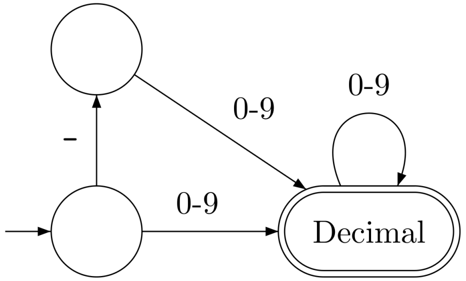


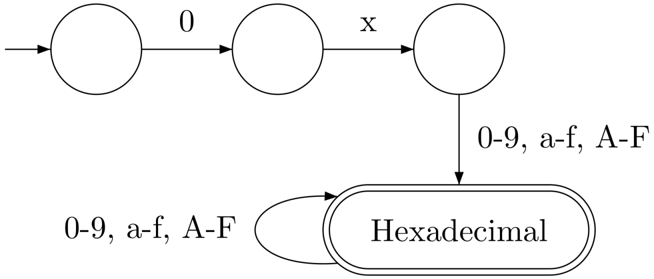


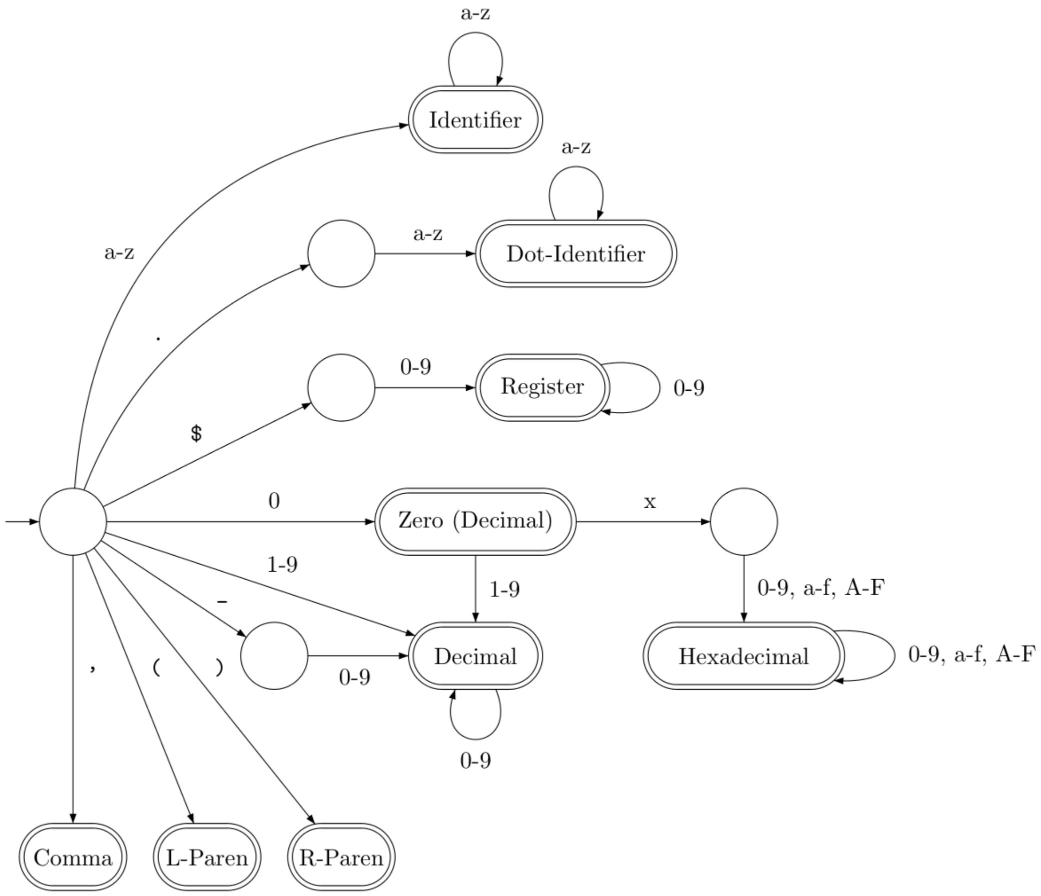


Decimal and Hexadecimal

- After reading "0", if we see "xFF", we should end up in the **Hexadecimal** state.

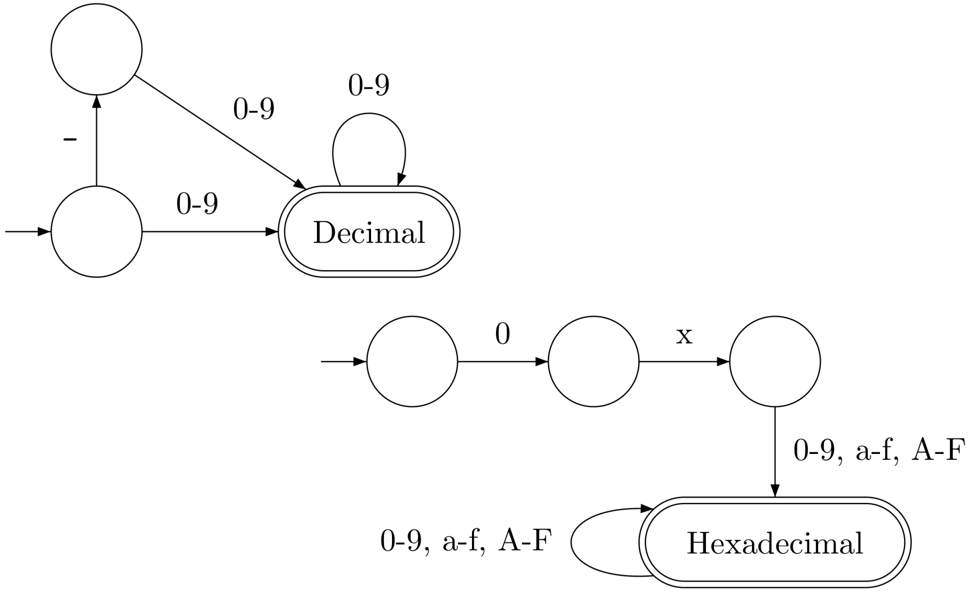


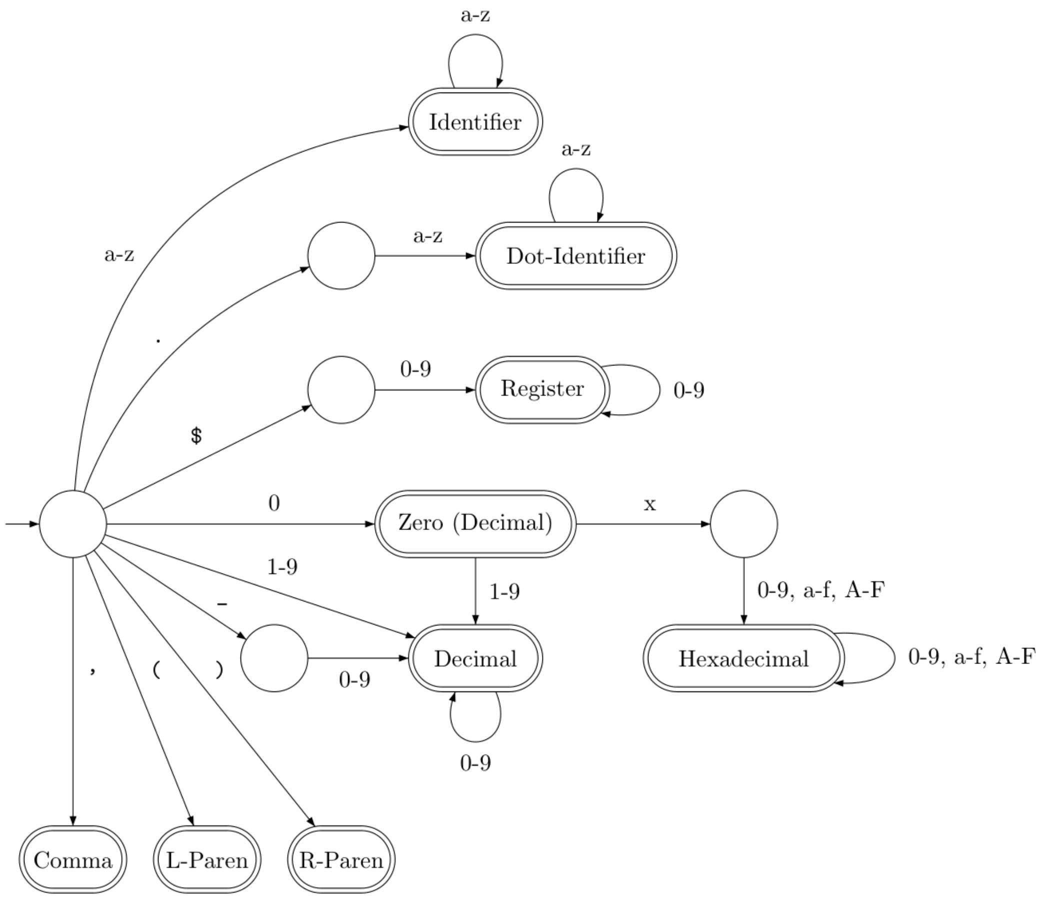




Decimal and Hexadecimal

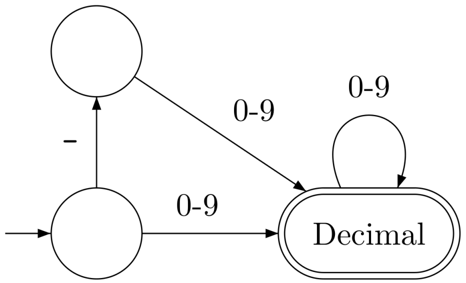
- But after reading "1", if we see "xFF", we get "1xFF" which is not a valid token at all.

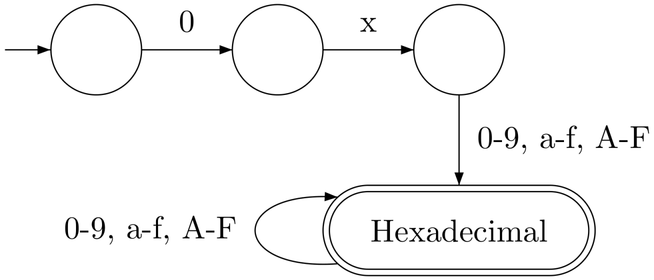


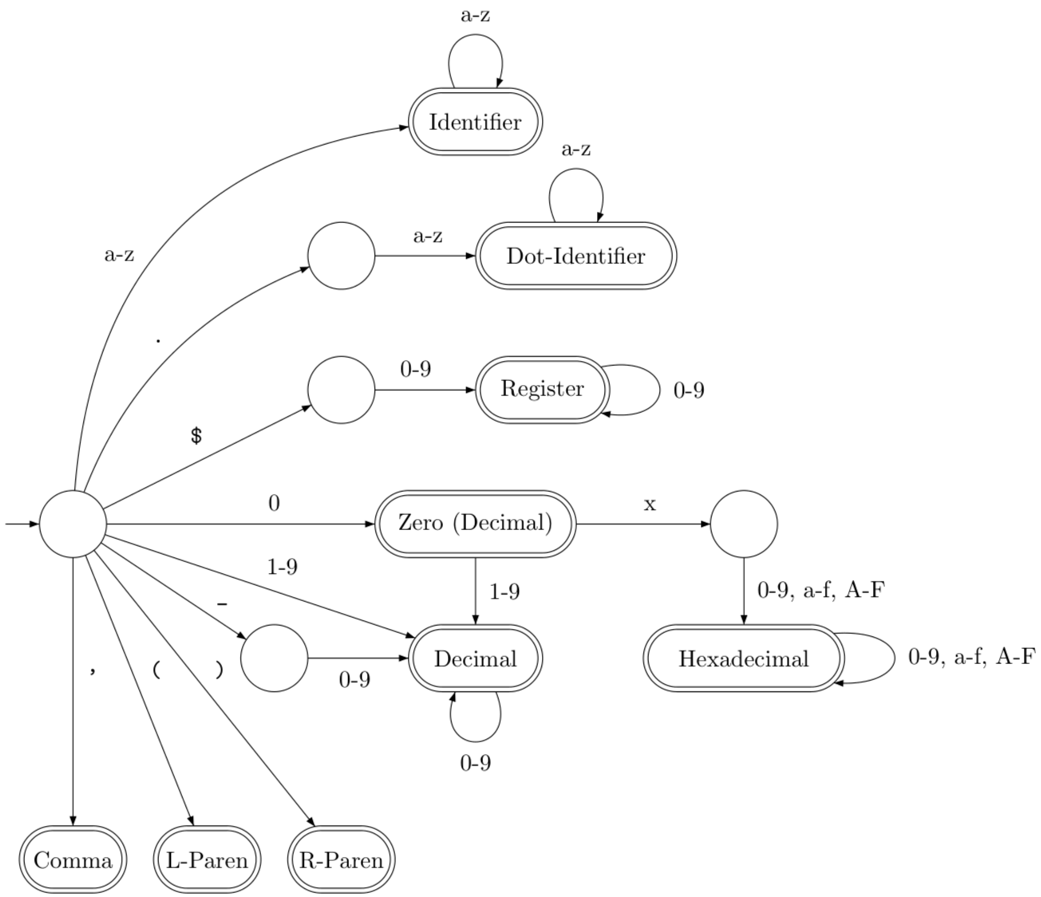


Decimal and Hexadecimal

- Therefore **"0" and "1" cannot go to the same state in the full DFA.** We need a separate state for "0".

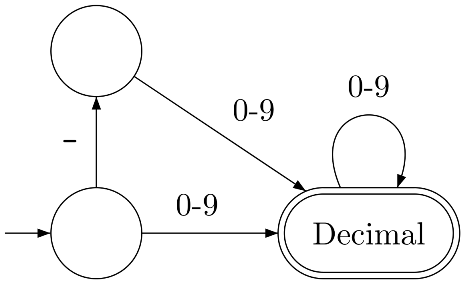


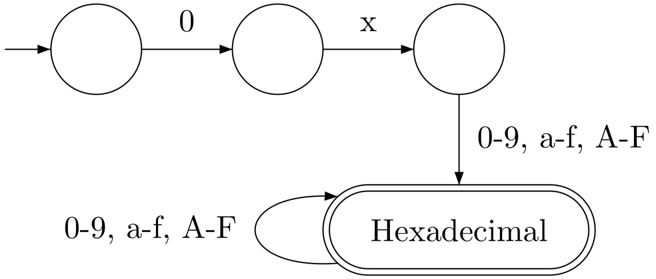


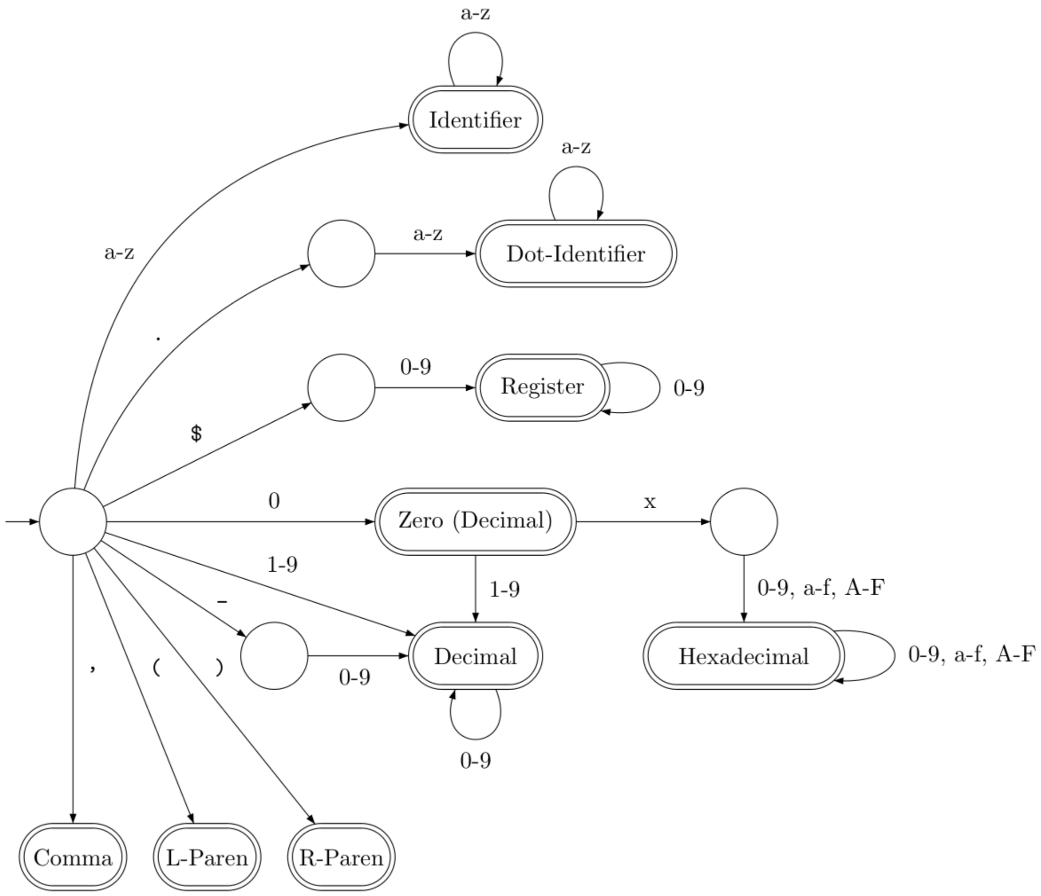


Decimal and Hexadecimal

- Note that our scanner should still output a **Decimal** token for zero.

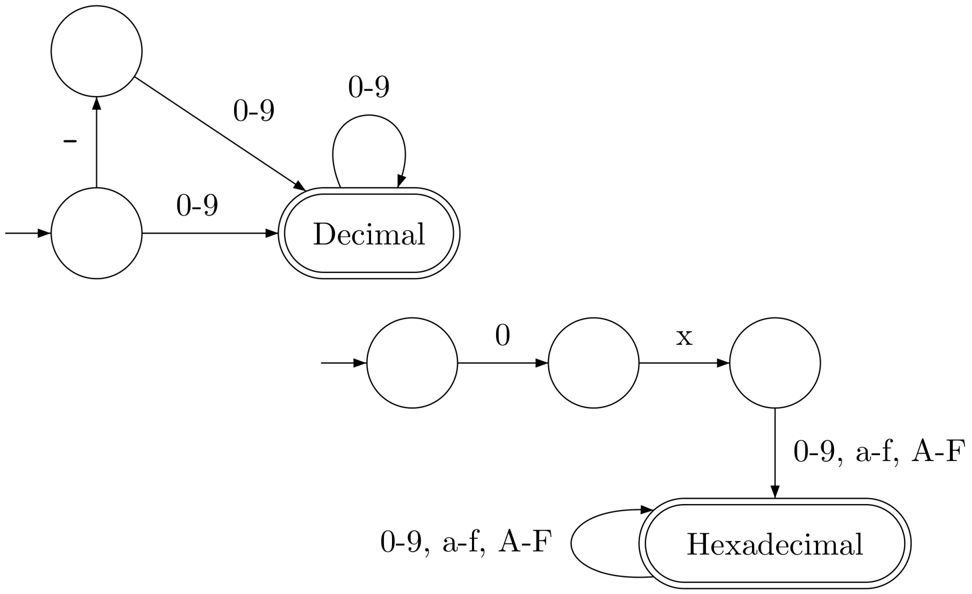


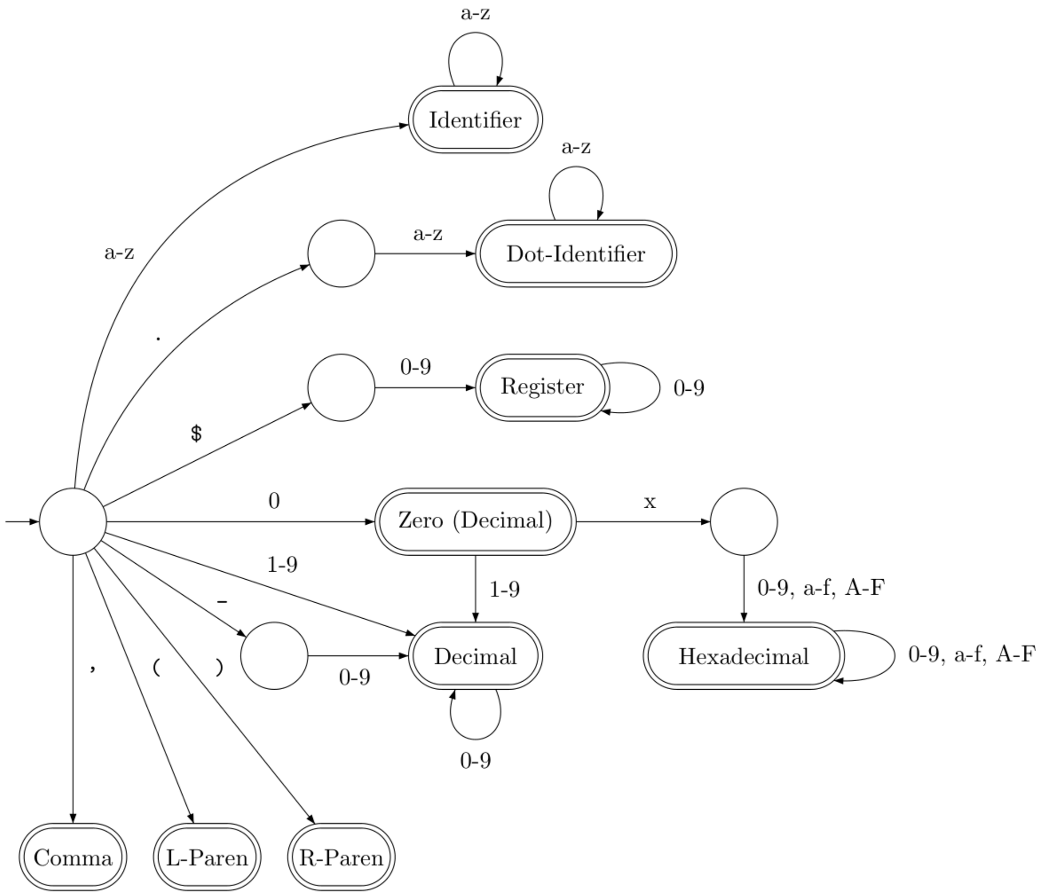




Decimal and Hexadecimal

- There is not always a perfect correspondence between token kinds and DFA states.





Parsing

- The result after scanning is that each line has been converted to a sequence of **tokens**.
- Parsing involves syntax checking (making sure the right tokens appear in the right order) and extracting information from each line.
- For example, suppose you see this token line:

  [Identifier "add"] [Register "$1"] [Comma ","] [Register "$2"] [Comma ","] [Register "$3"]

  - Look up the identifier "add" to determine the expected syntax (in this case, three registers separated by commas).
  - Read the following tokens to verify the syntax rules are followed.
  - Extract the information needed for Synthesis (instruction name and registers).

Parsing

- The result after scanning is that each line has been converted to a sequence of **tokens**.
- Parsing involves syntax checking (making sure the right tokens appear in the right order) and extracting information from each line.
- Some instructions are a little trickier than "add", e.g., "lw".
  - Both of these sequences of token kinds are valid for lw:
    ```
    Identifier Register Comma Decimal     L-Paren Register R-Paren
    Identifier Register Comma Hexadecimal L-Paren Register R-Paren
    ```
  - A Decimal/Hexadecimal token can be up to 32 bits in general, but must be in the 16 bit two's complement range for lw (extra range check needed).
  - A detailed syntax reference will be posted with the Assembler project.

Synthesis

- In the first version of our assembler, there's nothing to do for Semantic Analysis, so let's move on to Synthesis.
- Let's assume we have extracted the key information from each tokenized line, and we want to generate machine code.
  - add $3, $2, $1 → { instr: "add", s: 2, t: 1, d: 3 }
- Encoding for add $d, $s, $t:

```
000000 sssss ttttt ddddd 00000 100000
```

- Use a lookup table to figure out the last 6 bits (function bits).
- How do we handle the s, t and d values?

Synthesis

- One approach is to convert s, t and d to 5-character strings of 0s and 1s and create a string representation of the encoding.
  ```
  std::string instruction = "00000000010000010001100000100000";
  ```
- Then, use your solution to Question 2 to output the machine code.
- This *works*, but it's inefficient and wasteful because it involves a lot of unnecessary string operations.
- Instead of creating a *32-byte string*, it's much more efficient to store the encoding in a single *32-bit value*.
- We'll construct the encoding *as an integer!*

Encoding Instructions as Integers

- add \$3, \$2, \$1 → { instr: "add", s: 2, t: 1, d: 3 }
- Encoding for add \$3, \$2, \$1:

  `000000 00010 00001 00011 00000 100000`
- As a binary number, this is: $2^{22} + 2^{16} + 2^{12} + 2^{11} + 2^{5}$
- Let's do some math…
  - $$\begin{aligned} 2^{22} + 2^{16} + 2^{12} + 2^{11} + 2^{5} &= (2 \cdot 2^{21}) + (1 \cdot 2^{16}) + (3 \cdot 2^{11}) + 2^{5} \\ &= (s \cdot 2^{21}) + (t \cdot 2^{16}) + (d \cdot 2^{11}) + 2^{5} \end{aligned}$$
- We managed to express this value in terms of our register numbers!
- We could proceed like this, but there's a more idiomatic way.

Bitwise Operations

- Most programming languages offer these operations, which let you manipulate the bits in a binary value.
- **Bitwise OR:** x | y applies logical OR to each pair of bits in x and y.

```
int x = 10; int y = 12;
printf("%d\n", x | y); // prints 14
```

```
    1 0 1 0
  | 1 1 0 0
  ---------
    1 1 1 0
```

- **Bitwise AND:** x & y applies logical AND to each pair of bits in x and y.

```
    1 0 1 0
  & 1 1 0 0
  ---------
    1 0 0 0
```

- There is also **Bitwise XOR** (exclusive OR), denoted x ^ y.
- **Bitwise NOT:** ~x applies logical NOT to each bit in x.
  - For example, ~x + 1 takes the two’s complement of x.

Bitwise Operations: Shifting

- The last two bitwise operators are not based on logical operators.
- They are the **left bit shift** (<<) and **right bit shift** (>>) operators.
  - In C++, << and >> are also used for stream I/O. This has nothing to do with their use as bitwise operators.
- Left bit shift examples (8 bits):

```
  00001011 << 3
= 01011000

  00011011 << 6
= 11000000
```

- The left operand is "the sequence to shift".
- The right operand is "how far to shift" in bits.
- The number is padded with **zeroes** on the right.
- Overflowing bits typically get discarded.

Bit Shifting and Signedness

- With left bit shifting, the number is always padded with zeroes.
- For right bit shifting, there are two distinct kinds of shifts:
  - An **arithmetic right shift** pads with *whatever the leftmost bit is*. This will preserve the sign of a two's complement number.
  - A **logical right shift** pads with zeroes, which may change the sign.
- Examples using 8-bit two's complement values:

```
  10110001 >> 3          -79 >> 3
= 11110110             = -10
```

Arithmetic right shift

```
  10110001 >> 3          -79 >> 3
= 00010110             = 22
```

Logical right shift

Encoding "add" with Bitwise Operations

- You will need four pieces of information to encode add $d, $s, $t:
  - The values d, s and t as numbers.
  - The function bits for add. (Use a lookup table)
- The encoding of add $d, $s, $t has the form:

```
     000000 sssss ttttt ddddd 00000 100000
     ↑    ↑     ↑     ↑     ↑     ↑      ↑
Bit  31   26    21    16    11    6      0
```

- To compute the encoding:

```
int encoding = (s << 21) | (t << 16) | (d << 11) | fnBits["add"];
// where fnBits["add"] is 32 in decimal
```

How It Works (add $3, $2, $1)

```
int encoding = (s << 21) | (t << 16) | (d << 11) | fnBits["add"];
// where fnBits["add"] is 32 in decimal

s = 2         000000 00000 00000 00000 00000 000010
t = 1         000000 00000 00000 00000 00000 000001
d = 3         000000 00000 00000 00000 00000 000011
fnBits = 32   000000 00000 00000 00000 00000 100000

(2 << 21)     000000 00010 00000 00000 00000 000000
(1 << 16)     000000 00000 00001 00000 00000 000000
(3 << 11)     000000 00000 00000 00011 00000 000000
32            000000 00000 00000 00000 00000 100000

encoding      000000 00010 00001 00011 00000 100000
```

- Note the difference in order between the assembly (add $3, $2, $1) and machine code (s = 2, t = 1, d = 3) !!

Encoding an "sw" Instruction

- Let's now try to encode "sw $31, -4($30)".
- Encoding format for sw $t, i($s):

```
         101011 sssss ttttt iiiiiiiiiiiiiiii
         ↑    ↑     ↑     ↑                ↑
    Bit  31   26    21    16               0
```

- Note the difference in operand order again.
- The value i is encoded as a 16-bit two’s complement integer.
- We have opcode bits (first six bits) instead of function bits.
- First attempt (WRONG):

```
int encoding = (opBits["sw"] << 26) | (s << 21) | (t << 16) | i;
```

Encoding an "sw" Instruction

```
int encoding = (opBits["sw"] << 26) | (s << 21) | (t << 16) | i;
```

- What goes wrong when encoding "sw $31, -4($30)"?

```
opBits = 43  000000 00000 00000 0000000000101011
s = 30       000000 00000 00000 0000000000011110
t = 31       000000 00000 00000 0000000000011111
i = -4       111111 11111 11111 1111111111111100
```

Encoding an "sw" Instruction

```
int encoding = (opBits["sw"] << 26) | (s << 21) | (t << 16) | i;
```

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opBits = 43  000000 00000 00000 0000000000101011
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```

Encoding an "sw" Instruction

```
int encoding = (opBits["sw"] << 26) | (s << 21) | (t << 16) | i;
```

- What goes wrong when encoding "sw $31, -4($30)"?

```
opBits = 43   000000 00000 00000 0000000000101011
s = 30        000000 00000 00000 0000000000011110
t = 31        000000 00000 00000 0000000000011111
i = -4        111111 11111 11111 1111111111111100 (No!)

(43 << 26)    101011 00000 00000 0000000000000000
(30 << 21)    000000 11110 00000 0000000000000000
(31 << 16)    000000 00000 11111 0000000000000000
-4            111111 11111 11111 1111111111111100

encoding      111111 11111 11111 1111111111111100
```

- The 32-bit two's complement encoding of -4 overwrites everything.

Solution: Bit Masking

- You might think to store the offset "i" in a 16-bit two’s complement type, e.g., int16_t.
- This probably won’t work because C++ will automatically "promote" the 16-bit type when it is used alongside 32-bit types.
  - Maybe you can find a way to make it work if you study the promotion rules carefully, but there's an easier method!
- Use bitwise AND for **bit masking** (selectively zero out parts of a value).

```
-4              1111 1111 1111 1111 1111 1111 1111 1100
0xFFFF (mask)   0000 0000 0000 0000 1111 1111 1111 1111
(-4 & 0xFFFF)   0000 0000 0000 0000 1111 1111 1111 1100
```

- The 0 bits in the mask will zero out the corresponding bits in -4.
- The 1 bits in the mask will copy over the corresponding bits in -4.

Encoding an "sw" Instruction (with masking)

`int encoding = (opBits["sw"] << 26) | (s << 21) | (t << 16) | (i & 0xFFFF);`

- Encoding "sw $31, -4($30)":

```
opBits = 43   000000 00000 00000 0000000000101011
s = 30        000000 00000 00000 0000000000011110
t = 31        000000 00000 00000 0000000000011111
i = -4        111111 11111 11111 1111111111111100 (No?)

(43 << 26)    101011 00000 00000 0000000000000000
(30 << 21)    000000 11110 00000 0000000000000000
(31 << 16)    000000 00000 11111 0000000000000000
(-4 & 0xFFFF) 000000 00000 00000 1111111111111100 (Safe!)

encoding      101011 11110 11111 1111111111111100
```

- The same trick is needed for lw and for branch instructions.

Producing Output

- Once we have the encoding in a variable, producing output is easy…?

  ```
  int encoding = … ;
  ```

- The 32-bit (4-byte) encoding of "add $3, $2, $1" is: 00000000010000010001100000100000 which is 4266016 in decimal.
- std::cout << encoding; *will print out the 7-byte string "4266016".*
- This makes perfect sense. When you print an integer, you normally want an ASCII representation of the decimal value, and not the raw 4 bytes stored in the int variable.
- We need to find a way to **extract** each of the 4 bytes individually.

Extracting the Bytes

- We can use a combination of **right bit shifts** and **masking**.
- Example: Extract the leftmost byte of 0xC001BABE.

  In binary: 11000000 00000001 10111010 10111110
- We can do: (0xC001BABE >> 24) & 0xFF

```
0xC001BABE        11000000 00000001 10111010 10111110
0xC001BABE >> 24  11111111 11111111 11111111 11000000
0xFF              00000000 00000000 00000000 11111111
result            00000000 00000000 00000000 11000000
```

- We are assuming an *arithmetic right shift* (pad with leftmost bit) rather than a *logical right shift* (pad with zeroes).
  - The masking makes it so there is no difference.

Printing the Bytes

- Hopefully, you learned how to do this in Question 2.
- In Racket you can use the "write-byte" function.
- The equivalent in C++ is "std::putchar".
- You can also use std::cout, *if the byte is stored in a char variable.*
  - If it's in an int, it will be formatted and printed in decimal.
- In Racket, bit-masking is necessary, because write-byte will complain if you give it a value outside the range 0 to 255.
- In C++, putchar will truncate values larger than one byte to the lowest 8 bits automatically, so you can skip bit-masking.

A Simple Assembler

- We know enough now to write a simple MIPS assembler.
- We made the simplifying assumption that **every line contains an instruction or .word directive**, so that there is a one-to-one correspondence between assembly lines and machine code words.
- We'll now get back into MIPS programming and write programs that actually have interesting structures like conditionals and loops!
- However, we are not done with our assembler. We'll soon see that these programming techniques are somewhat inconvenient to work with, prompting us to extend our assembler with new features.