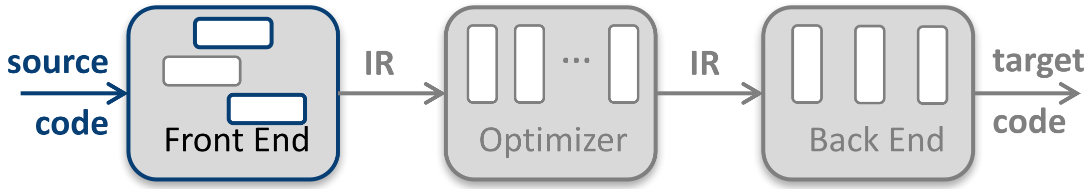
COMP 412
FALL 2017

Computing Inside The Parser

— Syntax-Directed Translation —

Comp 412



Chapter 4 in EaC2e

Where are we? Where are we going?

In the book:

- Chapter 3 focused on the membership question
  - Given a grammar *G*, is some sentence $s \in L(G)$?
  - We developed efficient techniques to recognize languages
  - To make useful tools, we need to go well beyond syntax
- Chapter 4 focuses on computing in the parser
  - Strong emphasis on attribute grammars in the written chapter
  - We will ignore that material & take a more ad-hoc, pragmatic approach
  - Lecture will emphasize the applications in compilers …
- Chapter 5 provides an overview of Intermediate Representations
  - Covered the representation of code in the last two lectures
  - Representation of name spaces coming in the near future
- Chapters 6, & 7 focus on the translation of language features into compiled code — runtime support & code shape
  - We will skip around wildly in these two chapters

Now We Know How To Build Parsers …

(The **COMP 412** answer)

What do we want to do with them?

- Parsers have many applications
  - Obvious answer is *"to build **IR** that will be compiled or interpreted"*
  - Reading markup languages: XML, EPUB, GML & KML, RSS and building data structures to represent the content of various ML documents
  - Reading other data representations (e.g., YAML) to transmit data in a rich and structured form
  - Reading in the results of other language processing tools: e.g., **EDIF**
- We use parsers to understand syntax

General Schema

- Read some input
- Build some data structures to model the input
- Perform some structured computation on the data structures

COMP 412 Is About Compiler Construction

What else does a compiler need to know about the input program?

- *Short answer:* everything

COMP 412 Is About Compiler Construction

What else does a compiler need to know about the input program?

- Compiler must assign storage to every item that needs storage
- Compiler must generate code for every construct that executes
- Compiler must plan resource allocation, use, & recycling
- Compiler must ensure coherent use of information (*types*)

The compiler is guided in this effort by the actual code, the language definition, and its knowledge about the runtime environment.

Meta Issue:

- The compiler does its work at *compile time*
- The compiler *emits code* that performs the work at *runtime*
- Keeping track of the times (*design, compile, run*) is critical to your understanding of the material

Example: Consistent Use of Values

To ensure consistent use of values, PLs introduce type systems

- Type systems allow the language designer to express constraints that are "deeper" than syntax
- Type systems allow the programmer to write down facts & intentions that are "deeper" than syntax

By comparing constraints against facts & expressed intentions, the compiler can often spot subtle and (otherwise) difficult to find errors

Type Checking

- Requires that the language have a well-designed type system
- Requires that the parser gather some base information on the code
- Requires that the semantic elaborator apply a set of inference rules
  - Inference rules range from simple (**C**) to complex (**ML**)

Example: Overloading of Names

To allow reuse of individual names, PLs introduce scoping rules

- Procedures start with a clean name space, as do blocks in some **PL**s
- Programmer can choose names, largely ignoring names used elsewhere
  - Exception: declared names of global values and interfaces
- The part of speech, identifier, does not encode enough information for the compiler to generate correct code

Compilers must recognize, model, & understand the scopes in a program

Compile-time and Runtime support

- Managing the applications name space requires support during translation (at *compile time*) and during execution (at *runtime*)
- Compilers build tables to encode knowledge at compile time
- Compilers emit code to build, maintain, & use runtime structures that support proper name resolution at runtime

Example: Storage Layout

To access data, running code needs an address in runtime RAM

- Running program cannot issue a load or a branch without an address
- Every item of code or data requires an address
  - Addresses are in the virtual address space of a new process
  - ***Meta Issue:*** that process won't exist until a user runs the compiled code
  - ***Meta Issue:*** code may run on different hardware and **OS** versions

The compiler must manage all decisions about storage layout, for the entire program (not just one procedure).

Storage Layout

- Semantic elaborator must lay out storage before it generates code
- For each item of code or data, the compiler must either:
  - Assign a symbolic address to each item, *or*
  - Implement a scheme whereby its address can be computed

Example: Separate Compilation

Programmers write code in modules & combine module into programs

- Compiler typically sees one module, or file, at a time
- Compilation for a module is, largely, context free
- Compiled code must link with other pre-compiled modules and/or pre-compiled library routines & system calls

Planning

- The compiler-writer must plan & standardize the ways in which the compiler will translate the source code, to create standard conventions for naming code & data, & for calling other procedures
  - Conventions for naming code and data segments
  - Conventions for calls & returns, for memory use, for system calls, …
- The compiler must implement those plans carefully & completely

Syntax-Directed Translation

All of these issues play into SDT

- Answers depend on computation over values, not parts of speech
- Questions & answers involve non-local information
- Questions and answers are “deeper” than syntax

How can we answer these questions?

- Use formal methods
  - Attribute grammars, rule-based systems
- Use *ad-hoc* techniques
  - Symbol tables, *ad-hoc* code

Formalisms work well for scanning & parsing. Real compilers use them.

For these “context-sensitive” issues, ad-hoc techniques dominate practice.

Example

Computing the value of an unsigned integer

Consider the simple grammar

1	*Number*	→	digit *DigitList*
2	*DigitList*	→	digit *DigitList*
3		|	epsilon

One obvious use of the grammar is to convert an **ASCII** string of the number to its integer value

- Build computation into parser
- An easy intro to *syntax-directed translation*

Example

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One obvious use of the grammar is to convert an **ASCII** string of the number to its integer value

- Build computation into parser
- An easy intro to *syntax-directed translation*

and its recursive-descent parser

```
boolean Number( ) {
   if (word = digit) then {
      word = NextWord( );
      return DigitList( );
   }
   else return false;
}

boolean DigitList( ) {
   if (word = digit) then {
      word = NextWord( );
      return DigitList( );
   }
   else return true;  /* epsilon case */
}
```

This example is for illustrative purposes. You don't need a CFG to recognize integers.

Example

Computing the value of an unsigned integer

Consider the simple grammar

1	*Number*	$\rightarrow$	digit *DigitList*
2	*DigitList*	$\rightarrow$	digit *DigitList*
3		|	epsilon

Any assembly programmer will tell you to accumulate the value, left to right, multiplying by the left-context value by 10 at each step.

e.g., 147 = (1 *10 + 4) * 10 + 7

and to get the value of character *d* by computing d – ‘0’

and its recursive-descent parser

```
boolean Number( ) {
   if (word = digit) then {
      word = NextWord( );
      return DigitList( );
   }
   else return false;
}

boolean DigitList( ) {
   if (word = digit) then {
      word = NextWord( );
      return DigitList( );
   }
   else return true;  /* epsilon case */
}
```

The programming “trick”, however, is undoubtedly how **atoi()** works.

Example

1	*Number*	→	<u>digit</u> *DigitList*
2	*DigitList*	→	<u>digit</u> *DigitList*
3		|	<u>epsilon</u>

Computing the value of an unsigned integer

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}
```

The Plan

1. Make *Number*() and *DigitList*() take value as an argument and return a (boolean,value) pair

1	*Number*	→	<u>digit</u> *DigitList*
2	*DigitList*	→	<u>digit</u> *DigitList*
3		|	<u>epsilon</u>

Example

Computing the value of an unsigned integer

```
boolean Number( ) {
   if (word = digit) then {
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boolean DigitList( ) {
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```

The Plan

1. Make *Number*() and *DigitList*() take value as an argument and return a (boolean,value) pair
2. Compute initial digit in *Number*()

Example

1	*Number*	→	digit *DigitList*
2	*DigitList*	→	digit *DigitList*
3		|	epsilon

Computing the value of an unsigned integer

```
boolean Number( ) {
   if (word = digit) then {
      word = NextWord( );
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   }
   else return false;
}

boolean DigitList( ) {
   if (word = digit) then {
      word = NextWord( );
      return DigitList( );
   }
   else return true;  /* epsilon case */
}
```

The Plan

1. Make *Number*() and *DigitList*() take value as an argument and return a (boolean,value) pair
2. Compute initial digit in *Number*()
3. Add second & subsequent digits in *DigitList*()

1	*Number*	→	<u>digit</u> *DigitList*
2	*DigitList*	→	<u>digit</u> *DigitList*
3		|	<u>epsilon</u>

Example

Computing the value of an unsigned integer

```
pair (boolean, int)  Number( value ) {
   if (word = digit) then {
      value = ValueOf( digit );
      word = NextWord( );
      return DigitList( value );
    }
    else return (false, invalid value);
}

pair (boolean, int)  DigitList( value ) {
   if (word = digit) then {
      value = value * 10 + ValueOf( digit );
      word = NextWord( );
      return DigitList( value );
    }
    else return (true, value);
}
```

The Plan

1. Make *Number*() and *DigitList*() take value as an argument and return a (boolean,value) pair
2. Compute initial digit in *Number*()
3. Add second & subsequent digits in *DigitList*()

```
Int ValueOf ( char d ) {
  return (int) d – (int) ‘0’;
}
```

Obvious, invented syntax for a pair

Example

Computing the value of an unsigned integer

Consider the simple grammar

1	*Number*	→	digit *DigitList*
2	*DigitList*	→	digit *DigitList*
3		|	epsilon

Ok, so it works with recursive descent.

What about an LR(1) parser?

Example

Computing the value of an unsigned integer

Consider the <u>left-recursive</u> grammar

1	*Number*	→	*DigitList*
2	*DigitList*	→	*DigitList* <u>digit</u>
3		|	<u>digit</u>

	ACTION		GOTO
	<u>digit</u>	<u>EOF</u>	*DigitList*
s_0	s 2	—	1
s_1	s 3	*acc*	—
s_2	r 3	r 3	—
s_3	r 2	r 2	—

We would like to augment the grammar with actions that compute the value of the number

- Cannot encode this computation into the context-free syntax
- Relies on the lexeme of each digit, rather than its part of speech

Example

Parse the number 976

State	Lookahead	Stack	Handle	Action
—	digit (9)	\$ 0	*—none—*	—
0	digit (9)	\$ 0	*—none—*	shift 2
2	digit (7)	\$ 0 9 2	*DL* → digit	reduce 3
1	digit (7)	\$ 0 *DL* 1	*—none—*	shift 3
3	digit (6)	\$ 0 *DL* 1 7 3	*DL* → *DL* digit	reduce 2
1	digit (6)	\$ 0 *DL* 1	*—none—*	shift 3
3	EOF	\$ 0 *DL* 1 6 3	*DL* → *DL* digit	reduce 2
1	EOF	\$ 0 *DL* 1	*Number* → *DL*	accept

	ACTION		GOTO
	digit	EOF	*DigitList*
s_0	s 2	—	1
s_1	s 3	*acc*	—
s_2	r 3	r 3	—
s_3	r 2	r 2	—

Notice that it reduces the 9 with *DL* → digit , and the others with *DL* → *DL* digit .

Rightmost derivation in reverse!

Example

Parse the number 976

State	Lookahead	Stack	Handle	Action
—	digit (9)	$ 0	*—none—*	—
0	digit (9)	$ 0	*—none—*	shift 2
2	digit (7)	$ 0 9 2	*DL* → digit	reduce 3
1	digit (7)	$ 0 *DL* 1	*—none—*	shift 3
3	digit (6)	$ 0 *DL* 1 7 3	*DL* → *DL* digit	reduce 2
1	digit (6)	$ 0 *DL* 1	*—none—*	shift 3
3	EOF	$ 0 *DL* 1 6 3	*DL* → *DL* digit	reduce 2
1	EOF	$ 0 *DL* 1	*Number* → *DL*	accept

Two cases that correspond to the actions in our recursive descent parser

- The leftmost digit should just set *value* to *ValueOf* (digit)
- Subsequent digits should compute *value* * 10 + *ValueOf* (digit)

Suggests that we perform the calculations when the parser reduces

Example

Parse the number 976

State	Lookahead	Stack	Handle	Action
—	digit (9)	$ 0	*—none—*	—
0	digit (9)	$ 0	*—none—*	shift 2
2	digit (7)	$ 0 9 2	*DL* → digit	reduce 3
1	digit (7)	$ 0 *DL* 1	*—none—*	shift 3
3	digit (6)	$ 0 *DL* 1 7 3	*DL* → *DL* digit	reduce 2
1	digit (6)	$ 0 *DL* 1	*—none—*	shift 3
3	EOF	$ 0 *DL* 1 6 3	*DL* → *DL* digit	reduce 2
1	EOF	$ 0 *DL* 1	*Number* → *DL*	accept

Computing on reductions

- Reduction by production 3 should set *value* to *ValueOf*(digit)
- Reduction by 2 should compute *value = value* * 10 + *ValueOf*(digit)

Example

Performing calculations on the reduce actions

State	Lookahead	Stack	Calculation	Action
—	digit (9)	$ 0		—
0	digit (9)	$ 0		shift 2
2	digit (7)	$ 0 9 2	*value* ← 9	reduce 3
1	digit (7)	$ 0 *DL* 1		shift 3
3	digit (6)	$ 0 *DL* 1 7 3	*value* ← *value* * 10 + 7	reduce 2
1	digit (6)	$ 0 *DL* 1		shift 3
3	EOF	$ 0 *DL* 1 6 3	*value* ← *value* * 10 + 6	reduce 2
1	EOF	$ 0 *DL* 1		accept

This style of computation is called *Ad Hoc Syntax-Directed Translation*

- Compiler writer provides code snippets for specific productions
- Parser actions determine specific actions & the overall sequence

SDT in Bison or Yacc

We specify SDT actions using a simple notation

1	*Number*	→	*DigitList*	{ \$\$ = \$1; }
2	*DigitList*	→	*DigitList* digit	{ \$\$ = \$1 * 10 + \$2; }
3		|	digit	{ \$\$ = *ValueOf*(digit); }

In Bison and Yacc, the compiler writer provides production-specific code snippets that execute when the parser reduces by that production

- Positional notation for the value associated with a symbol
  - \$\$ is the **LHS**; \$1 is the first symbol in the **RHS**; \$2 the second, …
- Compiler writer can put arbitrary code in these snippets
  - Solve a travelling salesman problem, compute **PI** to 100 digits, …
  - More importantly, they can compute on the lexemes of grammar symbols and on information derived and stored earlier in translation

Ad Hoc Syntax-Directed Translation

Why do we call this "*ad hoc*" syntax-directed translation?

- We have a formalism to specify syntax-directed translation schemes
  - Attribute grammars (see EaC2e, § 4.3)
  - An *attribute* is a value associated with an instance of a grammar symbol
    - → *Associated with a node in the parse tree*
- In formalism, compiler writer creates a specification & tools generate the code that performs the actual computation
  - Attribute-grammar evaluator generator (similar to parser generator)
  - Syntax-directed because the specification is written in terms of the grammar and the corresponding parse tree (or syntax tree)
  - Evaluator takes an "unattributed" tree and produces an "attributed tree"
- Attribute grammar systems have strengths & weaknesses
  - They have never quite become popular
  - If you are interested, Section 4.3 in EaC2e is a primer

Might **STOP**

We will focus on **ad hoc** SDT schemes. They are widely used in practice.

Fitting AHSDT into the **LR(1)** Skeleton Parser

```
stack.push(INVALID);
stack.push($s_0$);                    // initial state
word = scanner.next_word();
loop forever {
      s = stack.top();
      if ( ACTION[s,word] == "reduce $A \rightarrow \beta$" ) then {
        stack.popnum(2*|$\beta$|);   // pop 2*|$\beta$| symbols
        s = stack.top();
        stack.push(A);               // push LHS, A
        stack.push(GOTO[s,A]);  // push next state
      }
      else if ( ACTION[s,word] == "shift $s_i$" ) then {
            stack.push(word); stack.push($s_i$);
            word $\leftarrow$ scanner.next_word();
      }
      else if ( ACTION[s,word] == "accept"
                        & word == EOF )
            then break;
      else throw a syntax error;
}
report success;
```

Actions are taken on reductions

- Insert a call to *Work*() before the call to stack.popnum()
- *Work*() contains a case statement that switches on the production number
- Code in *Work*() can read items from the stack
  - → That is why it calls *Work*() before stack.popnum()

Fitting AHSDT into the **LR(1)** Skeleton Parser

```
stack.push(INVALID);
stack.push($s_0$);                    // initial state
word = scanner.next_word();
loop forever {
        s = stack.top();
        if ( ACTION[s,word] == "reduce $A \rightarrow \beta$" ) then {
          stack.popnum(2*|$\beta$|);   // pop 2*|$\beta$| symbols
          s = stack.top();
          stack.push($A$);              // push LHS, $A$
          stack.push(GOTO[s,$A$]);  // push next state
        }
        else if ( ACTION[s,word] == "shift $s_i$" ) then {
                stack.push(word); stack.push($s_i$);
                word $\leftarrow$ scanner.next_word();
        }
        else if ( ACTION[s,word] == "accept"
                              & word == EOF )
                then break;
        else throw a syntax error;
}
report success;
```

Passing values between actions

- Tie values to instances of grammar symbols
  - → Equivalent to parse tree nodes
- We can pass values on the stack
  - → Push / pop 3 rather than 2
  - → *Work*() takes the stack as input (*conceptually*) and returns the value for the reduction it processes
  - → *Shift* creates initial values

Fitting AHSDT into the **LR(1)** Skeleton Parser

```
stack.push(INVALID);
stack.push($s_0$);                          // initial state
word = scanner.next_word();
loop forever {
    s = stack.top();
    if ( ACTION[s,word] == "reduce $A \rightarrow \beta$" ) then {
      r = Work(stack, "$A \rightarrow \beta$")
      stack.popnum(3*|$\beta$|);  // pop 3*|$\beta$| symbols
      s = stack.top();            // save exposed state
      stack.push($A$);            // push A
      stack.push (r);             // push result of WORK()
      stack.push(GOTO[s,$A$]);    // push next state
    }
    else if ( ACTION[s,word] == "shift $s_i$" ) then {
        stack.push(word);
        stack.push(Initial Value);
        stack.push($s_i$);
        word ← scanner.next_word();
    }
    else if ( ACTION[s,word] == "accept"
                          & word == EOF )
        then break;
    else throw a syntax error;
}
report success;
```

- Modifications are minor
  - Insert call to *Work*()
  - Change the push() & pop() behavior
- Same asymptotic behavior as the original algorithm.
  - 50% more stack space
- Last obstacle is making it easy to write the code for *Work()*

*Note that, in **C**, the stack has some odd union type.*

Translating Code Snippets Into *Work*()

For each production, the compiler writer can provide a code snippet

{ *value* = *value* * *10* + *digit*; }

We need a scheme to name stack locations. Yacc introduced a simple one that has been widely adopted.

- $$ refers to the result, which will be pushed on the stack
- $1 is the first item on the productions right hand side
- $2 is the second item
- $3 is the third item, and so on …

The digits example above becomes

{ $$ = $1 * 10 + $2; }

Translating Code Snippets Into *Work()*

How do we implement *Work()*?

- *Work()* takes 2 arguments: the stack and a production number
- *Work()* contains a case statement that switches on production number
  - Each case contains the code snippet for a reduction by that production
  - The \$1, \$2, \$3 … macros translate into references into the stack
  - The \$\$ macro translates into the return value

```
…
if ( ACTION[s,word] == "reduce A→β" ) then {
        r = Work(stack, "A→β")
        stack.popnum(3*|β|);  // pop 3*|β| symbols
        s = stack.top();         // save exposed state
        stack.push(A);           // push A
        stack.push (r);          // push result of WORK()
        stack.push(GOTO[s,A]);  // push next state
      }
…
```

\$\$ translates to **r**

\$*i* translates to the stack location 3 *(|β| - *i* + 1) units down from stacktop

Note that β, *i*, *3*, and *1* are all constants so \$*i* can be evaluated to a compile-time constant