Intermediate Code Generation

Reading List:

Aho-Sethi-Ullman:

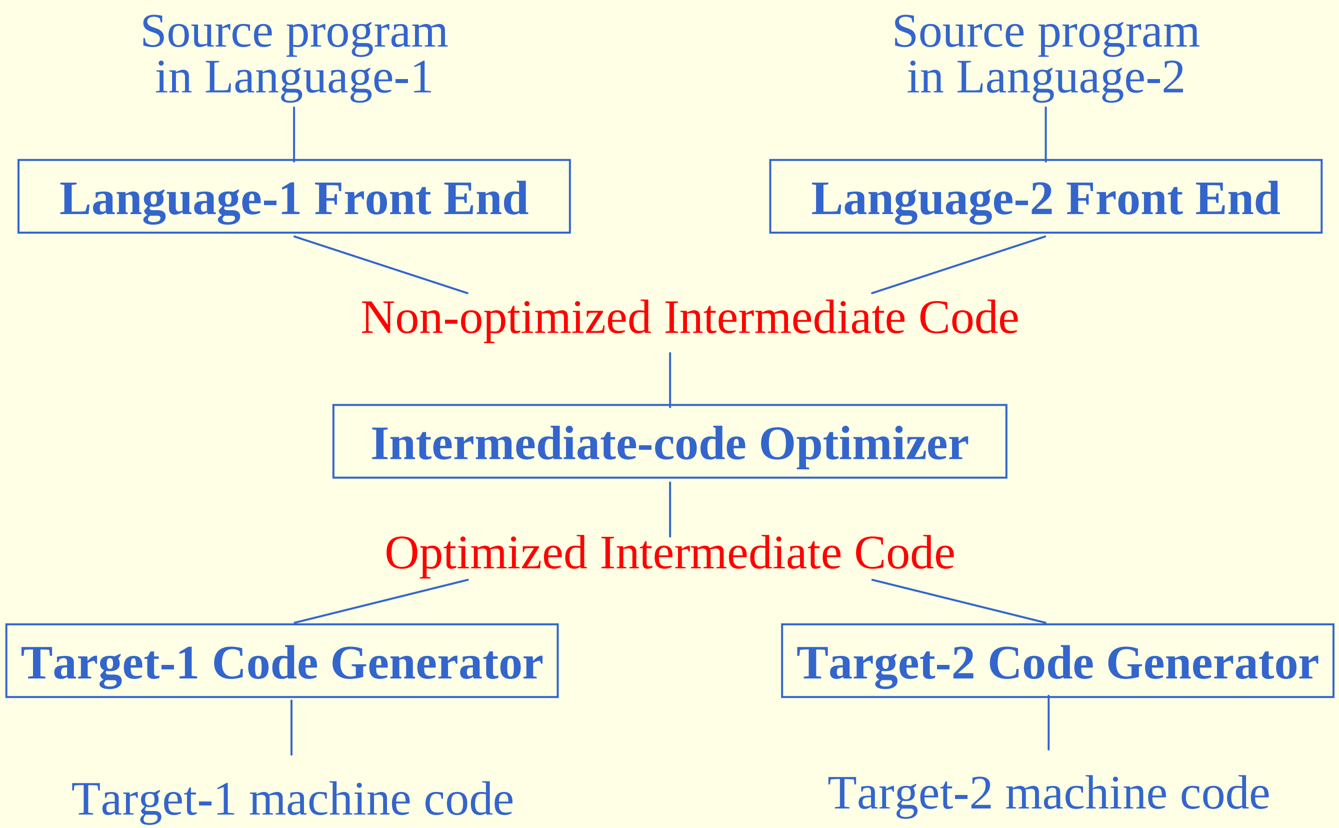
Chapter 2.3

Chapter 6.1 ~ 6.2

Chapter 6.3 ~ 6.10

(***Note***: *Glance through it only for intuitive understanding.)*

Component-Based Approach to Building Compilers

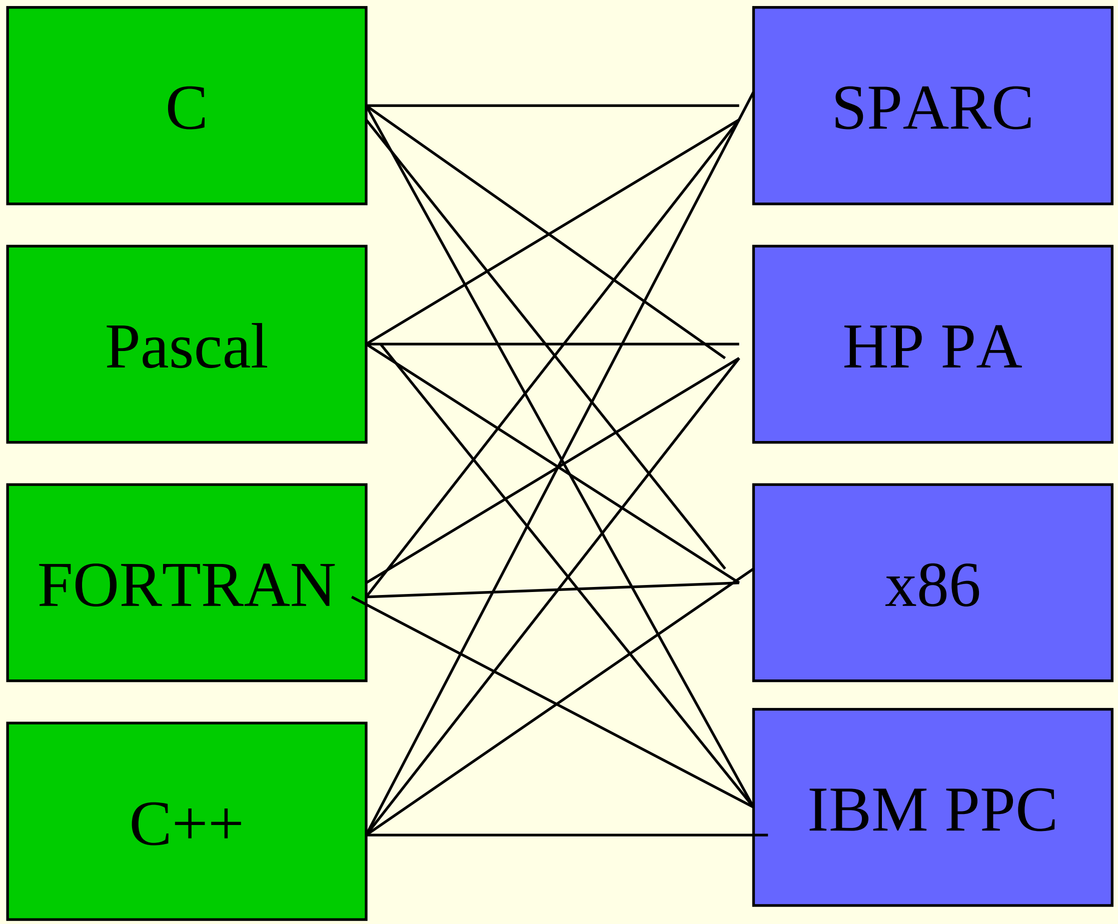


Intermediate Representation (IR)

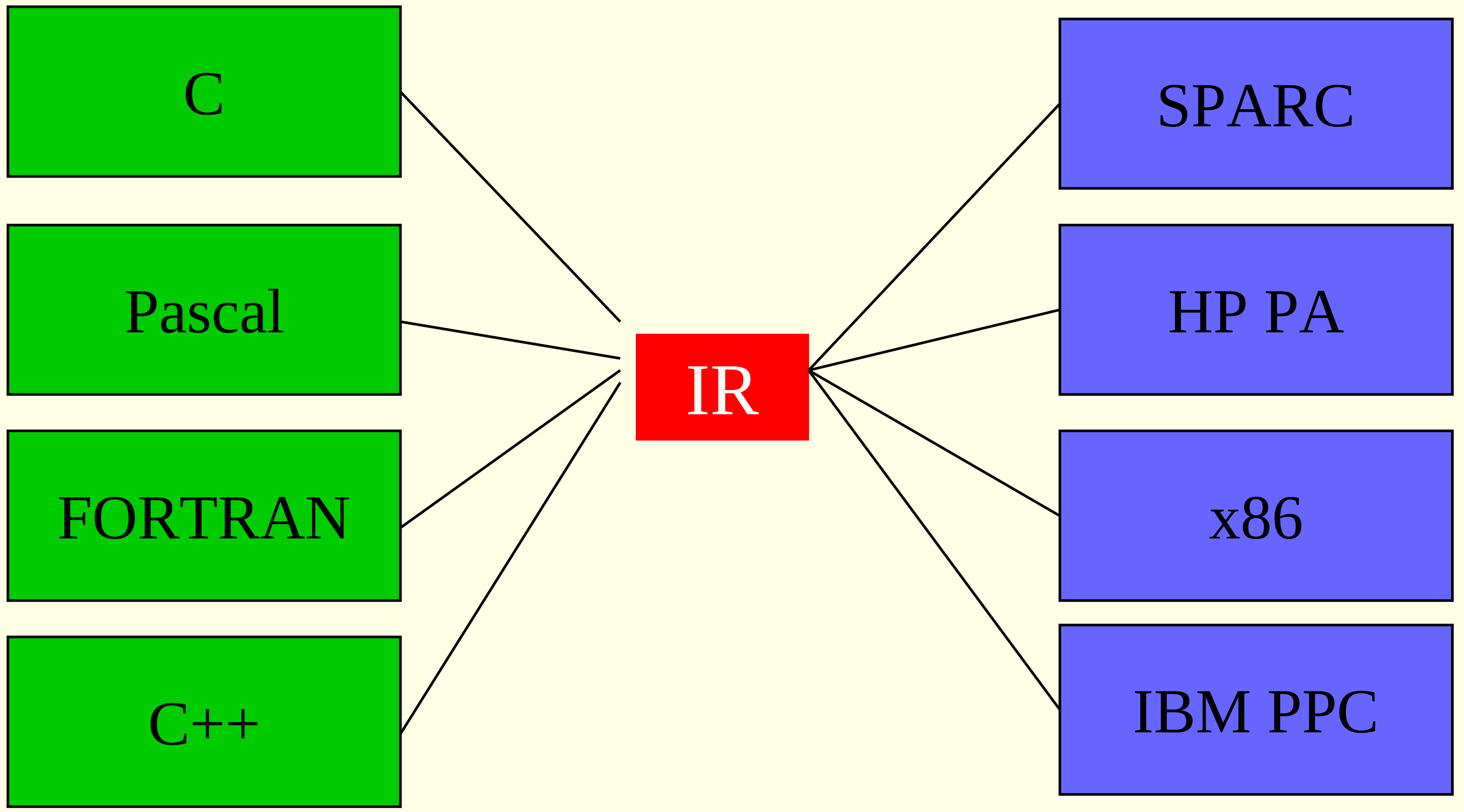
A kind of abstract machine language that can express the target machine operations without committing to too much machine details.

⌘Why IR ?

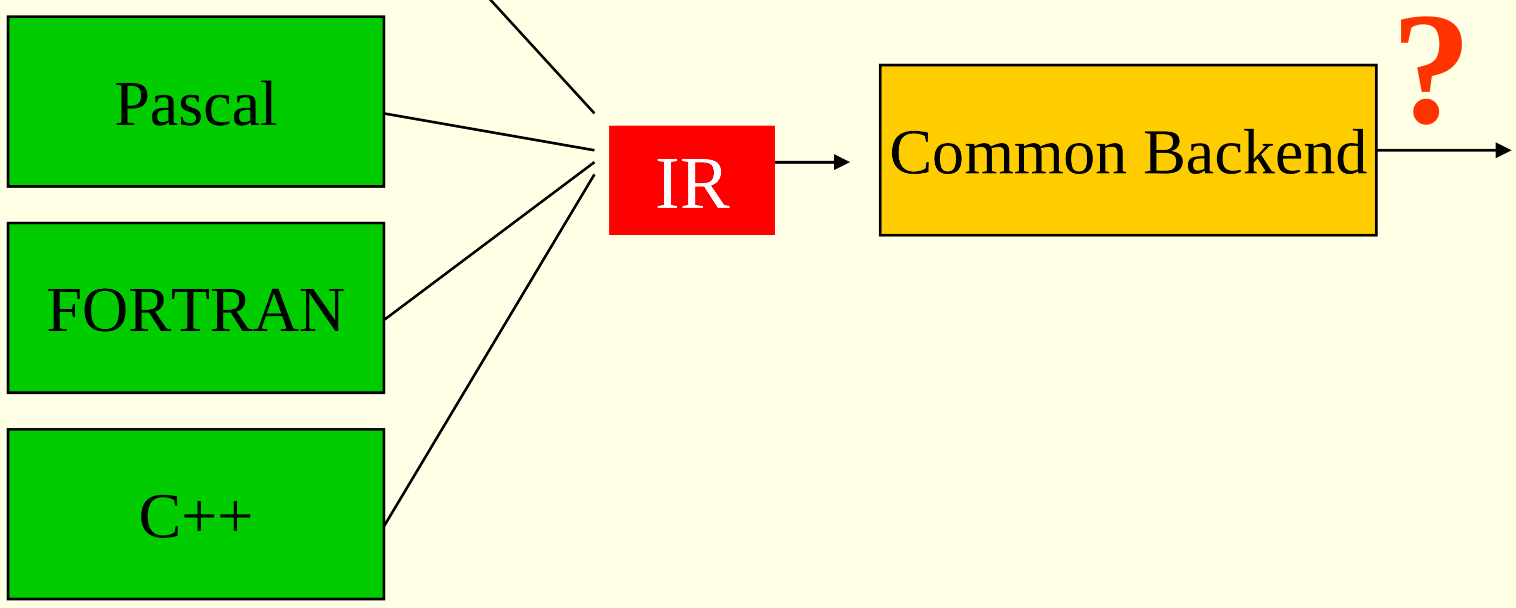
Without IR



With IR



With IR



Advantages of Using an Intermediate Language

1. ***Retargeting*** - Build a compiler for a new machine by attaching a new code generator to an existing front-end.
2. ***Optimization*** - reuse intermediate code optimizers in compilers for different languages and different machines.

Note: the terms “intermediate code”, “intermediate language”, and “intermediate representation” are all used interchangeably.

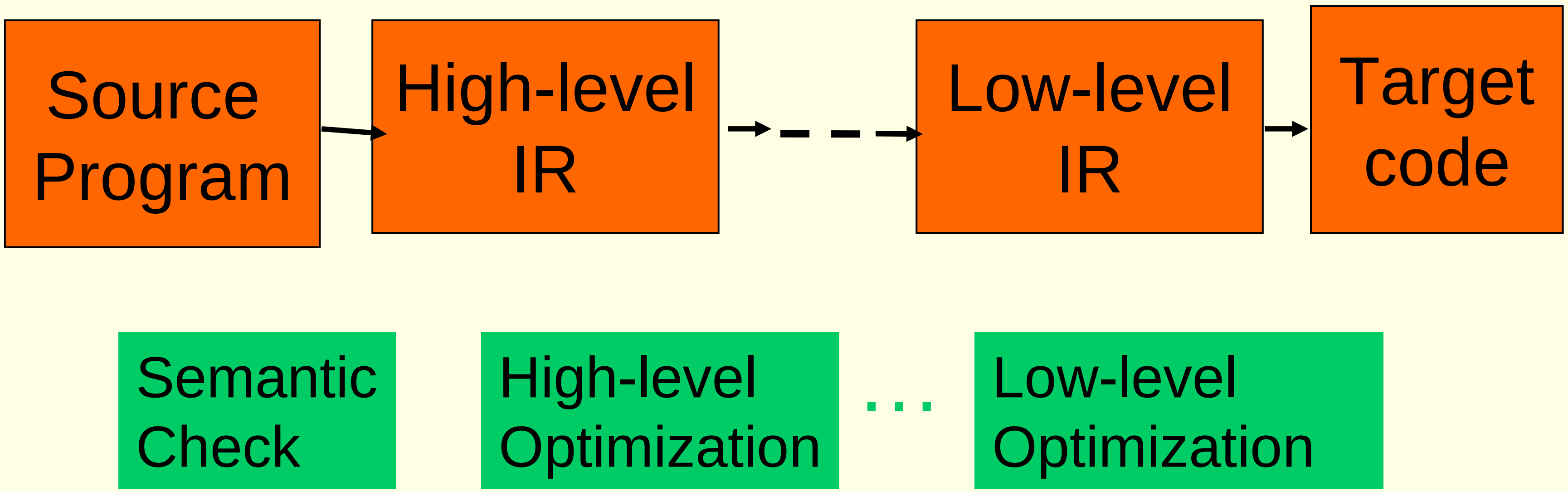
Issues in Designing an IR

- Whether to use an existing IR
  - if target machine architecture is similar
  - if the new language is similar
- Whether the IR is appropriate for the kind of optimizations to be performed
  - e.g. speculation and predication
  - some transformations may take much longer than they would on a different IR

Issues in Designing an IR

- Designing a new IR needs to consider
  - Level (how machine dependent it is)
  - Structure
  - Expressiveness
  - Appropriateness for general and special optimizations
  - Appropriateness for code generation
  - Whether multiple IRs should be used

Multiple-Level IR



Using Multiple-level IR

Translating from one level to another in the compilation process

- Preserving an existing technology investment
- Some representations may be more appropriate for a particular task.

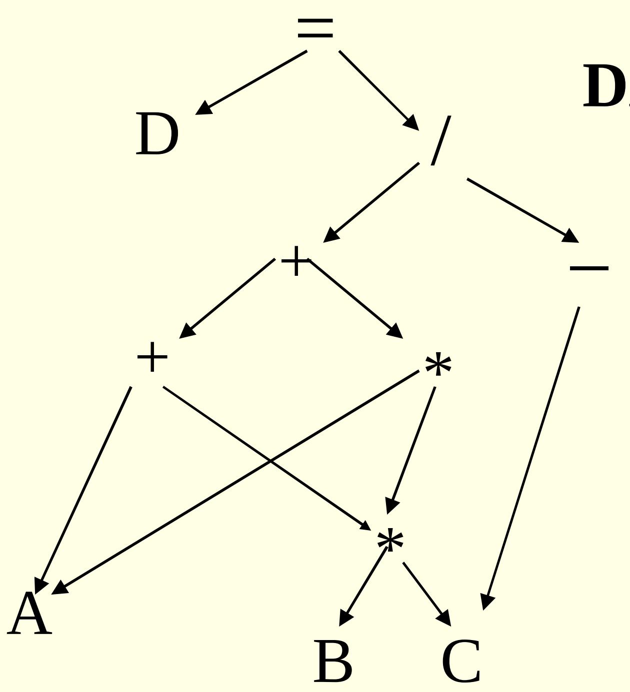
Commonly Used IR

- Possible IR forms
  - Graphical representations: such as syntax trees, AST (Abstract Syntax Trees), DAG
  - Postfix notation
  - Three address code
  - SSA (Static Single Assignment) form
- IR should have individual components that describe simple things

DAG Representation

A variant of syntax tree.

Example: D = ((A+B*C) + (A*B*C))/ -C



DAG: Direct Acyclic Graph

Postfix Notation (PN)

A mathematical notation wherein every operator follows all of its operands.

Examples:

The PN of expression 9* (5+2) is 952+*

How about (a+b)/(c-d) ?   ab+cd-/

Postfix Notation (PN) – Cont'd

Form Rules:

1. **If E is a variable/constant, the PN of E is E itself**
2. **If E is an expression of the form E_1 op E_2, the PN of E is $E_1'E_2'$op (E_1' and E_2' are the PN of E_1 and E_2, respectively.)**
3. **If E is a parenthesized expression of form (E_1), the PN of E is the same as the PN of E_1.**

Three-Address Statements

A popular form of intermediate code used in optimizing compilers is three-address statements.

Source statement:

$$x = a + b * c + d$$

Three address statements with temporaries t_1 and t_2:

$$t_1 = b * c$$
$$t_2 = a + t_1$$
$$x = t_2 + d$$

Three Address Code

The general form

x := y **op** z

x,y,and z are names, constants, compiler-generated temporaries

op stands for any operator such as +,-,…

x*5-y might be translated as

t1 := x * 5

t2 := t1 - y

Syntax-Directed Translation Into Three-Address

Temporary

- In general, when generating three-address statements, the compiler has to create new temporary variables (temporaries) as needed.
- We use a function *newtemp( )* that returns a new temporary each time it is called.
- Recall Topic-2: when talking about this topic

Syntax-Directed Translation Into Three-Address

- The syntax-directed definition for ***E*** in a production **id := *E*** has two attributes:

1. ***E.place*** - the location (variable name or offset) that holds the value corresponding to the nonterminal
2. ***E.code*** - the sequence of three-address statements representing the code for the nonterminal

Example Syntax-Directed Definition

term ::= ID
{ term.place := ID.place ; term.code = “” }

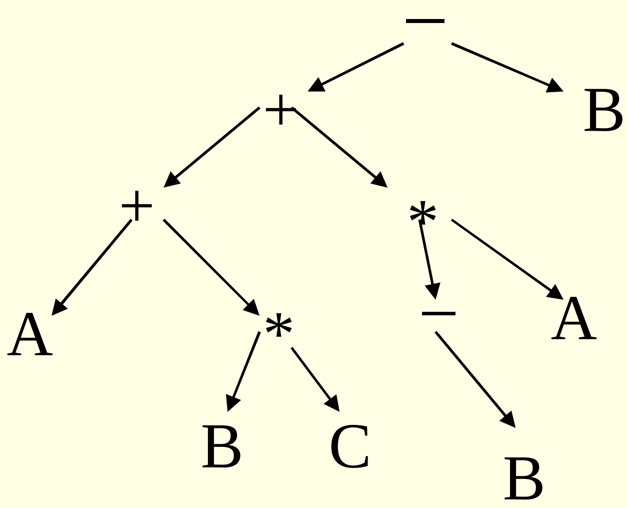
$term_1$ ::= $term_2$ * ID
{$term_1$.place := newtemp( );
$term_1$.code := $term_2$.code || ID.code ||*
gen($term_1$.place ‘:=‘ $term_2$.place ‘*’ ID.place}

expr ::= term
{ expr.place := term.place ; expr.code := term.code }

$expr_1$ ::= $expr_2$ + term
{ $expr_1$.place := newtemp( )
expr1.code := $expr_2$.code || term.code ||+
gen($expr_1$.place ‘:=‘ $expr_2$.place ‘+’ term.place
}

Syntax tree vs. Three address code

Expression: (A+B*C) + (-B*A) - B

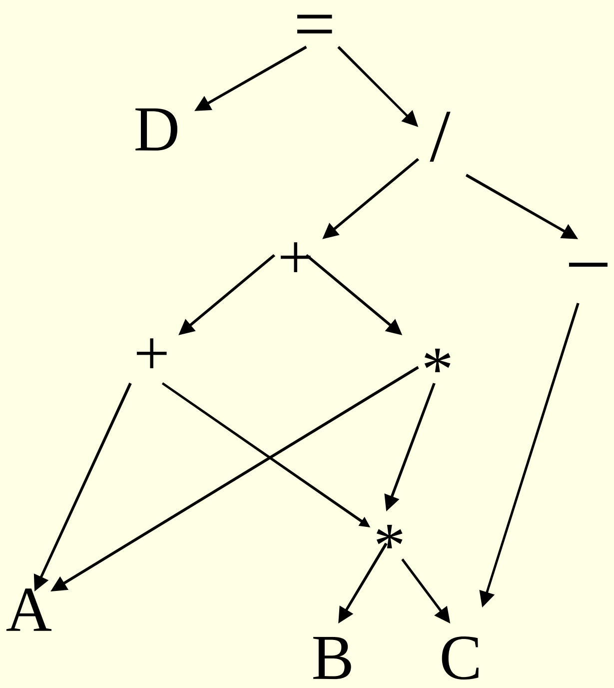


T1 := B * C
T2 = A + T1
T3 = - B
T4 = T3 * A
T5 = T2 + T4
T6 = T5 – B

Three address code is a linearized representation of a syntax tree (or a DAG) in which explicit names (temporaries) correspond to the interior nodes of the graph.

DAG vs. Three address code

Expression: D = ((A+B*C) + (A*B*C))/ -C



T1 := A
T2 := C
T3 := B * T2
T4 := T1+T3
T5 := T1*T3
T6 := T4 + T5
T7 := – T2
T8 := T6 / T7
D := T8

T1 := B * C
T2 := A+T1
T3 := A*T1
T4 := T2+T3
T5 := – C
T6 := T4 / T5
D := T6

Question: Which IR code sequence is better?

Implementation of Three Address Code

- Quadruples
  - Four fields: op, arg1, arg2, result
    - Array of struct {op, *arg1, *arg2, *result}
  - x:=y op z is represented as op y, z, x
  - arg1, arg2 and result are usually pointers to symbol table entries.
  - May need to use many temporary names.
  - Many assembly instructions are like quadruple, but arg1, arg2, and result are real registers.

Implementation of Three Address Code (Con't)

- Triples
  - Three fields: op, arg1, and arg2. Result is implicit.
  - arg1 and arg2 are either pointers to the symbol table or index/pointers to the triple structure.

Example: d = a + (b*c)

1	*	b, c
2	+	a, (1)
3	assign	d, (2)

Problem in reorder the codes?

  - No explicit temporary names used.
  - Need more than one entries for ternary operations such as x:=y[i], a=b+c, x[i]=y, … etc.

IR Example in Open64 – WHIRL

The Open64 uses a tree-based intermediate representation called WHIRL, which stands for Winning Hierarchical Intermediate Representation Language.

WHIRL

- Abstract syntax tree based
- Symbol table links, map annotations
- Base representation is simple and efficient
- Used through several phases with lowering
- Designed for multiple target architectures

From WHIRL to CGIR
An Example

```
int    *a;
int     i;
int     aa;
aa  =  a[i];
```

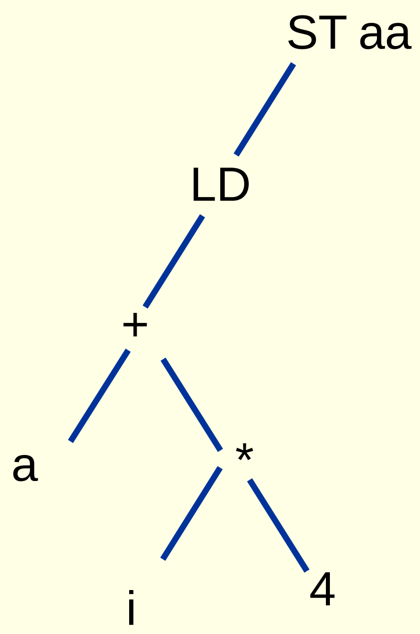
(a) Source

```
      U4U4LDID 0 <2,1,a> T<47,anon_ptr.,4>
        U4U4LDID 0 <2,2,i> T<8,.predef_U4,4>
        U4INTCONST 4 (0x4)
      U4MPY
    U4ADD
  I4I4ILOAD 0 T<4,.predef_I4,4> T<47,anon_ptr.,4>
I4STID 0 <2,3,aa> T<4,.predef_I4,4>
```

(b) Whirl

From WHIRL to CGIR

An Example



(c) WHIRL

T_1 = sp + &a;

T_2 = ld T_1

T_3 = sp + &i;

T_4 = ld T_3

$T_6 = T_4$ << 2

$T_7 = T_6$

$T_8 = T_2 + T_7$

T_9 = ld T_8

T_{10} = sp + &aa

:= st T_{10} T_9

(d) CGIR

```
      U4U4LDID 0 <2,1,a> T<47,anon_ptr.,4>
        U4U4LDID 0 <2,2,i> T<8,.predef_U4,4>
        U4INTCONST 4 (0x4)
      U4MPY
    U4ADD
   I4I4ILOAD 0 T<4,.predef_I4,4> T<47,anon_ptr.,4>
I4STID 0 <2,3,aa> T<4,.predef_I4,4>
```

WHIRL

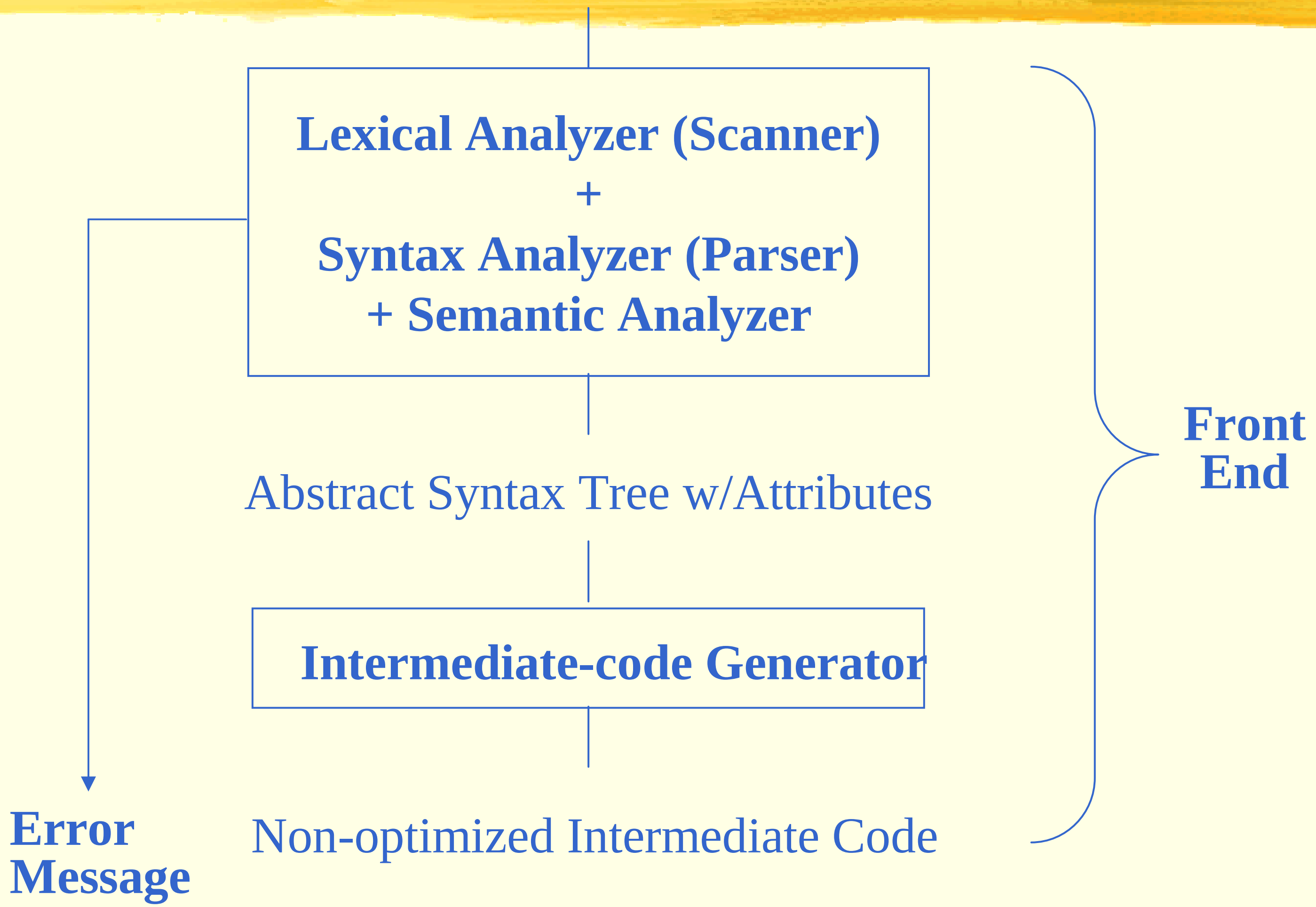
```
(insn 8 6 9 1 (set (reg:SI 61 [ i.0 ])
        (mem/c/i:SI (plus:SI (reg/f:SI 54 virtual-stack-vars)
                (const_int -8 [0xfffffffffffffff8])) [0 i+0 S4 A32])) -1 (nil)
    (nil))

(insn 9 8 10 1 (parallel [
            (set (reg:SI 60 [ D.1282 ])
                (ashift:SI (reg:SI 61 [ i.0 ])
                    (const_int 2 [0x2])))
            (clobber (reg:CC 17 flags))
        ]) -1 (nil)
    (nil))

(insn 10 9 11 1 (set (reg:SI 59 [ D.1283 ])
        (reg:SI 60 [ D.1282 ])) -1 (nil)
    (nil))

(insn 11 10 12 1 (parallel [
            (set (reg:SI 58 [ D.1284 ])
                (plus:SI (reg:SI 59 [ D.1283 ])
                    (mem/f/c/i:SI (plus:SI (reg/f:SI 54 virtual-stack-vars)
                            (const_int -12 [0xfffffffffffffff4])) [0 a+0 S4 A32])))
            (clobber (reg:CC 17 flags))
        ]) -1 (nil)
    (nil))

(insn 12 11 13 1 (set (reg:SI 62)
        (mem:SI (reg:SI 58 [ D.1284 ]) [0 S4 A32])) -1 (nil)
    (nil))

(insn 13 12 14 1 (set (mem/c/i:SI (plus:SI (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffffffffffc])) [0 aa+0 S4 A32])
        (reg:SI 62)) -1 (nil)
    (nil))
```

GCC RTL

Differences

- gcc rtl describes more details than whirl
- gcc rtl already assigns variables to stack
- actually, WHIRL needs other symbol tables to describe the properties of each variable. Separating IR and symbol tables makes WHIRL simpler.
- WHIRL contains multiple levels of program constructs representation, so it has more opportunities for optimization.

Summary of Front End



The Phases of a Compiler

Position := initial + rate * 60

↓

lexical analyzer

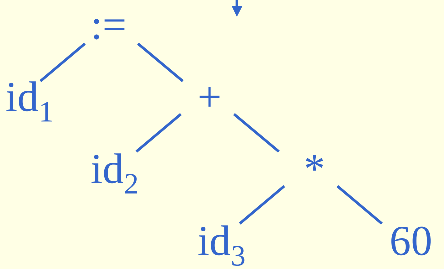
↓

$id_1 := id_2 + id_3 * 60$

↓

syntax analyzer

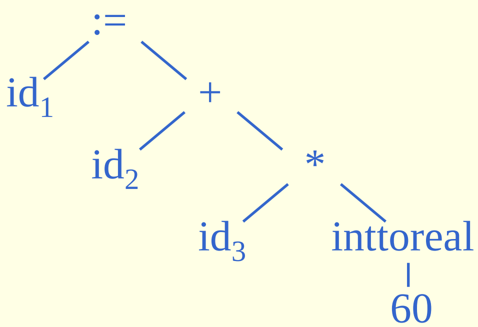
↓



↓

semantic analyzer

↓



↓

intermediate code generator

↓

temp1 := inttoreal (60)
temp2 := id_3 * temp1
temp3 := id_2 + temp2
id1 := temp3

↓

code optimizer

↓

temp1 := id_3 * 60.0
id1 := id_2 + temp1

↓

code generator

↓

```
MOVF   id3,    R2
MULF   #60.0,  R2
MOVF   id2,    R1
ADDF   R2,     R1
MOVF   R1,     id1
```

Summary

1. **Why IR**
2. **Commonly used IR**
3. **IRs of Open64 and GCC**