Intermediate Code Generation

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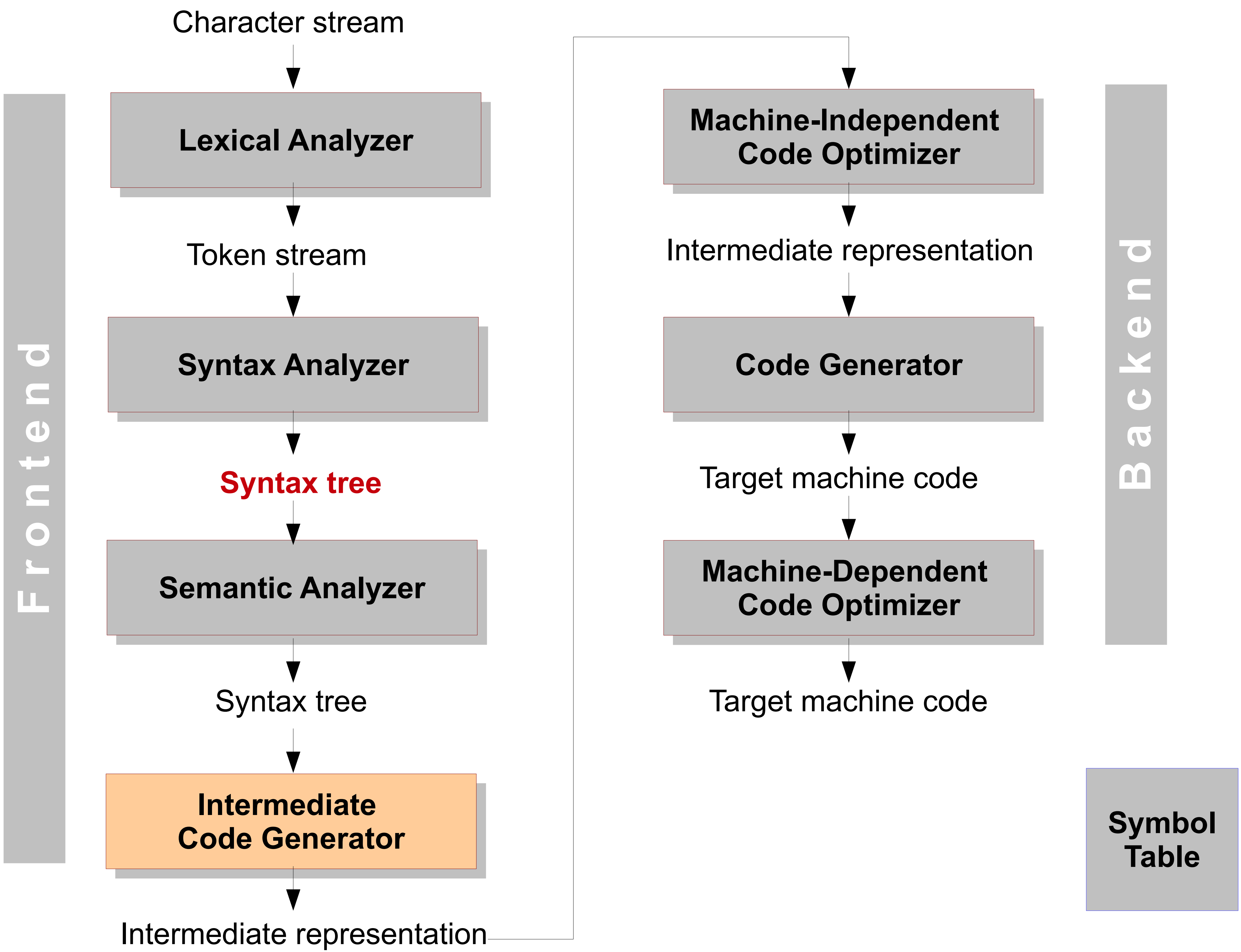


Character stream
Lexical Analyzer
Token stream
Syntax Analyzer
Syntax tree
Semantic Analyzer
Syntax tree
Intermediate Code Generator
Intermediate representation
Frontend
Machine-Independent Code Optimizer
Intermediate representation
Code Generator
Target machine code
Machine-Dependent Code Optimizer
Target machine code
Backend
Symbol Table

Agenda

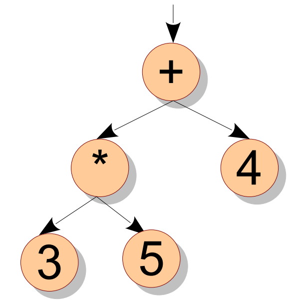
- IR forms
  - 3AC, 2AC, 1AC
  - SSA
- IR generation
  - Types
  - Declarations
  - Assignments
  - Conditionals
  - Loops

Role of IR Generator

- To act as a glue between front-end and backend (or source and machine codes).
- To lower abstraction from source level.
  - To make life simple.
- To maintain some high-level information.
  - To keep life interesting.
- Complete some syntactic checks, perform more semantic checks.
  - e.g. *break* should be inside loop or *switch* only.

Representations

- Syntax Trees
  - Maintains structure of the construct
  - Suitable for high-level representations



- Three-Address Code
  - Maximum three addresses in an instruction
  - Suitable for both high and low-level representations
- Two-Address Code
- …
  - e.g. Java

```
t1 = 3 * 5
t2 = t1 + 4
```

3AC

```
mult 3, 5
add 4
```

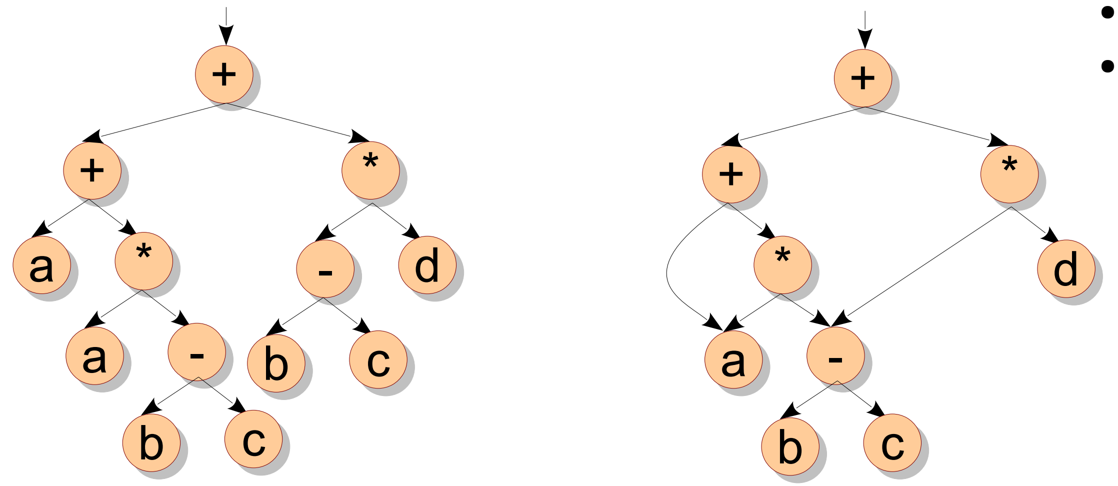
2AC

```
push 3
push 5
mult
push 4
add
```

1AC or stack machine

Syntax Trees and DAGs

a + a * (b – c) + (b – c) * d



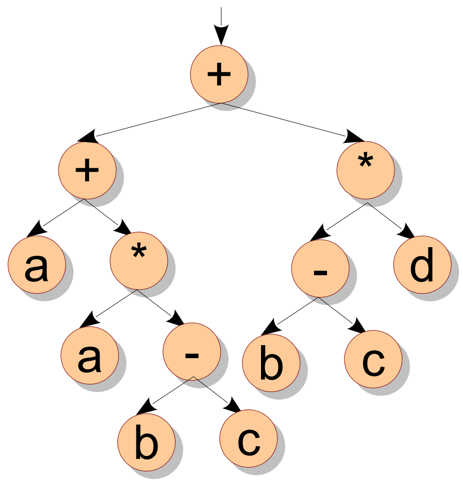
- Trees represent replicated expressions.
- Cannot optimize processing.
- For optimizations, the structure changes to a DAG.

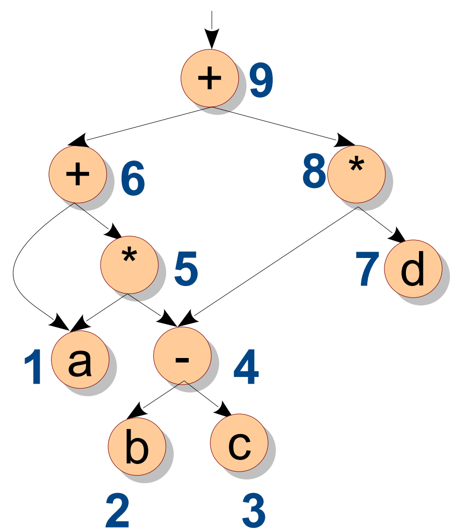
Production	Semantic Rules
E → E + T	if (!($$.node = find($1, $2, $3))) $$.node = new Op($1.node, '+', $3.node)
E → E - T	if (!($$.node = find($1, $2, $3))) $$.node = new Op($1.node, '-', $3.node)
E → T	$$.node = $1.node
T → (E)	$$.node = $2.node
T → *id*	if (!($$.node = find($1))) $$.node = new Leaf($1)
T → *num*	if (!($$.node = find($1))) $$.node = new Leaf($1)

A small problem:
subgraph isomorphism is NP-complete.

Value Numbering

a + a * (b – c) + (b – c) * d





A small problem:
subgraph isomorphism is NP-complete.

But that is in general!

- Uniquely identifies a node in the DAG (hashing).
- A node with value number V contains children of numbers < V.
- Thus, an ordering of the DAG is possible.
- This corresponds to an evaluation order of the underlying expression.
- For inserting $\mathbf{l\ op\ r}$, search for node $\mathbf{op}$ with children $\mathbf{l}$ and $\mathbf{r}$.
- **Classwork:** Find value numbering for $\mathbf{a + b + a + b}$.

Three-Address Code

- An address can be a name, constant or temporary.
- Assignments x = y op z; x = op y.
- Copy x = y.
- Unconditional jump goto L.
- Conditional jumps if x relop y goto L.
- Parameters param x.
- Function call y = call p.
- Indexed copy x = y[i]; x[i] = y.
- Pointer assignments x = &y; x = *y; *x = y.

3AC Representations

- Triples
- Quadruples

Instructions cannot be reordered.

Instructions can be reordered.

Assignment statement: **a = b * - c + b * - c;**

				op	arg1	arg2	result
t1	=	minus c		minus	c		t1
t2	=	b * t1		*	b	t1	t2
t3	=	minus c		minus	c		t3
t4	=	b * t3		*	b	t3	t4
t5	=	t2 + t4		+	t2	t4	t5
a	=	t5		=	t5		a

	op	arg1	arg2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)

3AC Representations

- Triples
- Quadruples

Instructions cannot be reordered.

Assignment statement: **a = b * - c + b * - c;**

(0)
(1)
(2)
(3)
(4)
(5)

(2)
(3)
(0)
(1)
(4)
(5)

	op	**arg1**	**arg2**
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)

Indirect triples can be reordered

SSA

- **Classwork**: Allocate registers to variables.
- Some observations
  - Definition of a variable *kills* its previous definition.
  - A variable's use refers to its *most recent* definition.
  - A variable holds a register for a long time, if it is *live* longer.

$$
\begin{aligned}
p_1 &= a + b\\
q_1 &= p_1 - c\\
p_2 &= q_1 * d\\
p_3 &= e - p_2\\
q_2 &= p_3 + q_1
\end{aligned}
$$

$$
\begin{aligned}
p &= a + b\\
q &= p - c\\
p &= q * d\\
p &= e - p\\
q &= p + q
\end{aligned}
$$

a	r1	r1
b	r2	r2
p	r3	r1, r2, r2
c	r4	r2
q	r5	r1, r1
d	r6	r2
e	r7	r3

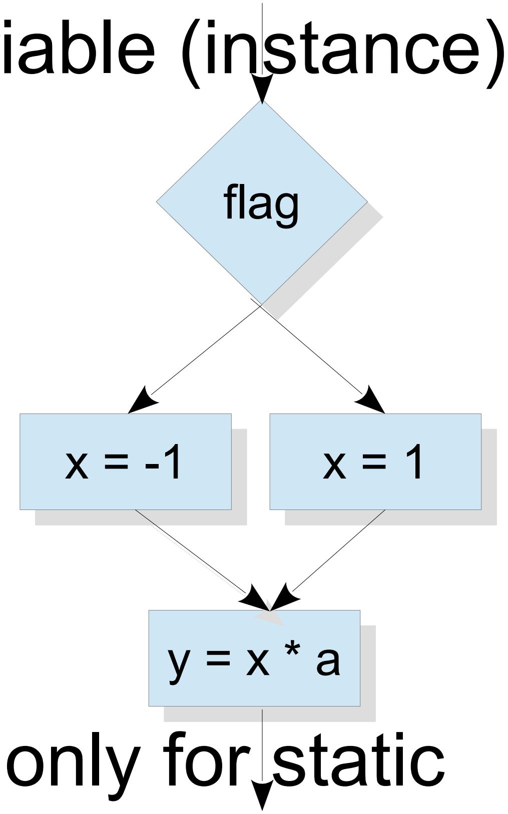
Can r3 be avoided?

SSA

- Static Single Assignment
  - An IR
  - Each definition refers to a different variable (instance)

```
if (flag)
    x = -1;
else
    x = 1;
y = x * a;
```

if (flag)
$\quad x_1 = -1;$
else
$\quad x_2 = 1;$
$x_3 = \Phi(x_1, x_2)$
$y = x_3 * a;$



- A phi node is an abstract node.
  - Not present in executable code. Used only for static analysis.
  - Phi indicates selection of one of the values.
  - It is an idempotent operator.

SSA

- **Classwork**: Find SSA form for the following program fragment.

```
x = 0;
for (i = 0; i < N; ++i) {
    x += i;
    i = i + 1;
    x--;
}
x = x + i;
```

$$
\begin{array}{l}
x_1 = 0; \\
i_1 = 0; \\
\text{L1:} \\
\quad i_{13} = \Phi(i_1, i_3); \\
\quad \text{if } (i_{13} < N) \; \{ \\
\qquad x_{13} = \Phi(x_1, x_3); \\
\qquad x_2 = x_{13} + i_{13}; \\
\qquad i_2 = i_{13} + 1; \\
\qquad x_3 = x_2 - 1; \\
\qquad i_3 = i_2 + 1; \\
\qquad \text{goto L1;} \\
\quad \} \\
x_4 = \Phi(x_1, x_3); \\
x_5 = x_4 + i_{13};
\end{array}
$$

Agenda

- IR forms
  - 3AC, 2AC, 1AC
  - SSA
- IR generation
  - Types
  - Declarations
  - Assignments
  - Conditionals
  - Loops

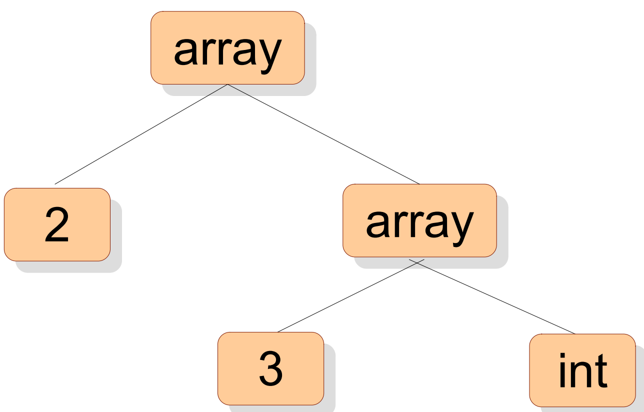
Language Constructs

to generate IR

- Declarations
  - Types (int, int [], struct, int *)
  - Storage qualifiers (array expressions, const, static)
- Assignments
- Conditionals, switch
- Loops
- Function calls, definitions

SDT Applications

- Finding type expressions
  - int a[2][3] is array of 2 arrays of 3 integers.
  - in functional style: *array(2, array(3, int))*



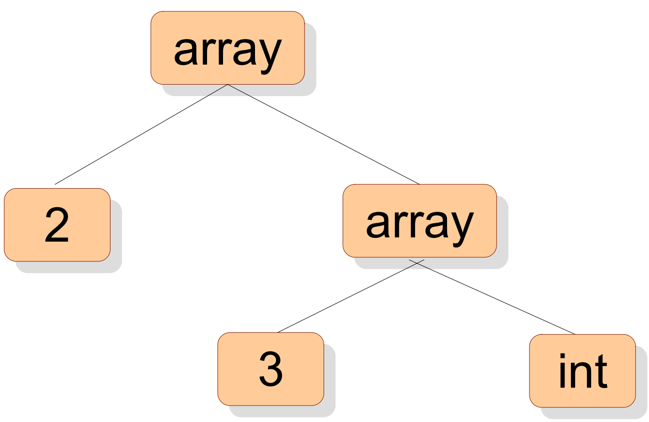
Production	Semantic Rules
T → B id C	T.t = C.t C.i = B.t
B → *int*	B.t = *int*
B → *float*	B.t = *float*
C → [num] C_1	C.t = array(num, C_1.t) C_1.i = C.i
C → ε	C.t = C.i

Classwork: Write productions and semantic rules for computing types and finding their widths in bytes.

SDT Applications

Width can also be computed using S-attributed SDT.

- Finding type expressions
  - int a[2][3] is array of 2 arrays of 3 integers
  - in functional style: *array(2, array(3, int))*



Production	Semantic Rules
T → B id C	T.t = C.t; T.sw = C.sw; C.i = B.t; C.iw = B.sw;
B → *int*	B.t = *int;* B.sw = 4;
B → *double*	B.t = *double*; B.sw = 8;
C → [num] C_1	C.t = array(num, C_1.t); C_1.i = C.i; C.sw = C_1.sw * num.value;
C → ε	C.t = C.i; C.sw = C.iw;

Classwork: Write productions and semantic rules for computing types and finding their widths in bytes.

Types

- Types encode:
  - Storage requirement (number of bits)
  - Storage interpretation (meaning)
  - Valid operations (manipulation)

  For instance,
  - 1100..00 may be char[4], int, float, int[1], …

Type Equivalence

Compare against assembly code.

- Two types are **structurally equivalent** iff one of the following conditions is true.
  1. They are the same basic type.
  2. They are formed by applying the same construction to structurally equivalent types.
  3. One is a type name that denotes the other.

Name equivalence

typedef

- *int a[2][3]* is not equivalent to *int b[3][2]*;
- *int a* is not equivalent to *char b[4]*;
- *struct {int, char}* is not equivalent to *struct {char, int}*;
- *int ** is not equivalent to *void **.

Type Equivalence

- Name equivalence is easy to check, but is strict.

```
typedef int NumCarsType;
typedef int NumTrucksType;
NumCarsType ncars = 2;
NumTrucksType ntrucks = 2;
if (ncars == ntrucks):
```
Type error

- Structural equivalence permits this, but then:

  DoublyLinkedListNode == BSTNode: No type error

- A language may follow different schemes for different types.
  - C follows structural equivalence for primitives, but name equivalence for structures.
- May permit char [32] to be type-equiv. to char [24] for ease of use.

Type Checking

- Type expressions are checked for
  - Correct code
  - Security aspects
  - Efficient code generation
  - …
- Compiler determines that type expressions conform to a collection of logical rules, called as the *type system* of the source language.
- *Type synthesis*: if f has type $s \rightarrow t$ and x has type s, then expression $f(x)$ has type t.
- *Type inference*: if $f(x)$ is an expression, and if f has type $\alpha \rightarrow \beta$, then x has type α.

Type Checking

- *Type synthesis*: if f has type $s \rightarrow t$ and x has type s, then expression $f(x)$ has type t.
  - C++ templates
  - A template defines a skeleton. A type gets constructed when we define a variable vector<int> v; This involves type synthesis.
- *Type inference*: if $f(x)$ is an expression, and if f has type $\alpha \rightarrow \beta$, then x has type α.
  - auto x = 5;
  - Add(1, 2); Add(1.0, 2.0); Add(list1, list2);

Type System

- Potentially, everything can be checked dynamically...
  - if type information is carried to execution time.
  - Source: typeid.cpp
- A *sound* static type system eliminates the need for dynamic type checking.
- A language implementation is *strongly typed* if a compiler guarantees that the valid source programs (it accepts) will run without type errors.

Type Conversions

- $\text{int a} = 10; \text{ float b} = 2 * \text{a};$
- **Widening** conversions are safe.
  - $\text{int32} \rightarrow \text{long32} \rightarrow \text{float} \rightarrow \text{double}$
  - Automatically done by compiler, called *coercion*.
- **Narrowing** conversions may not be safe.
  - $\text{int} \rightarrow \text{char}$
  - Usually, enforced by the programmers, called *casts*.
  - Sometimes, deferred until runtime, $\text{dyn\_cast}<...>$.

Declarations

- When declarations are together, a single offset on the stack pointer suffices.
  - int x, y, z; fun1(); fun2();
- Otherwise, the translator needs to keep track of the current offset.
  - int x; fun1(); int y, z; fun2();
- A similar concept is applicable for fields in structs (when methods are present).
- Blocks and Nestings
  - Need to push the current environment and pop.

Language Constructs

to generate IR

- Declarations
  - Types (int, int [], struct, int *)
  - Storage qualifiers (array expressions, const, static)
- Assignments
- Conditionals, switch
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Expressions

- We have studied expressions at length.
- To generate 3AC, we will use our grammar and its associated SDT to generate IR.
- For instance, $\mathrm{a} = \mathrm{b} + \text{-c}$ would be converted to

$$\mathrm{t1} = \mathrm{minus\ c}$$

$$\mathrm{t2} = \mathrm{b} + \mathrm{t1}$$

$$\mathrm{a} = \mathrm{t2}$$

Array Expressions

- For instance, create IR for c + a[i][j].
- This requires us to know the types of a and c.
- Say, c is an integer (4 bytes) and a is int [2][3].
- Then, the IR is

```
t1 = i * 12         ; 3 * 4 bytes
t2 = j * 4          ; 1 * 4 bytes
t3 = t1 + t2        ; offset from a
t4 = a[t3]          ; assuming base[offset] is present in IR.
t5 = c + t4
```

Array Expressions

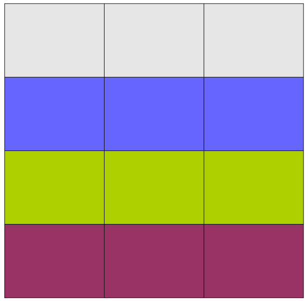
- a[5] is a + 5 * sizeof(type)
- a[i][j] for a[3][5] is
  a + i * 5 * sizeof(type) + j * sizeof(type)
- This works when arrays are zero-indexed.
- **Classwork:** Find array expression to be generated for accessing a[i][j][k] when indices start with low, and array is declared as type a[10][20][30].
- **Classwork:** What all computations can be performed at compile-time?
- **Classwork:** What happens for malloc'ed arrays?

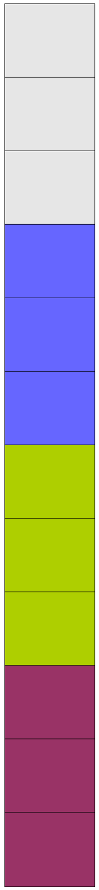
Array Expressions

```
void fun(int a[ ][ ]) {
        a[0][0] = 20;
}
void main() {
        int a[5][10];
        fun(a);
        printf("%d\n", a[0][0]);
}
```

ERROR: type of formal parameter 1 is incomplete

We view an array to be a D-dimensional matrix. However, for the hardware, it is simply single dimensional.

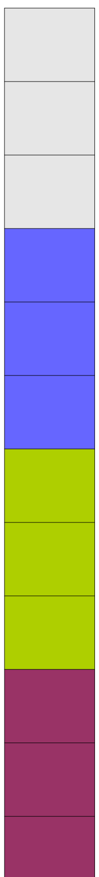


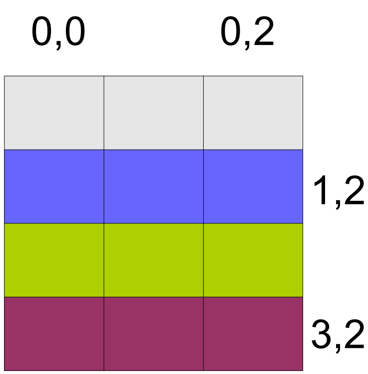


- How to optimize computation of the offset for a long expression a[i][j][k][l] with declaration as int a[w4][w3][w2][w1]?
  - $i * w3 * w2 * w1 + j * w2 * w1 + k * w1 + l$
  - Use Horner's rule: $((i * w3 + j) * w2 + k) * w1 + l$

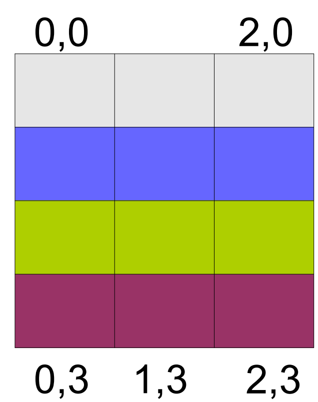
Array Expressions

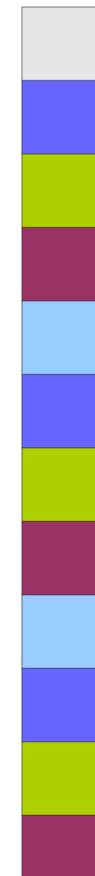
- In C, C++, Java, and so far, we have used *row-major* storage.
  - All elements of a row are stored together.





- In Fortran, we use *column-major* storage format.
  - each column is stored together.





IR for Array Expressions

- L → id [E] | L [E]

// maintain three attributes: type, addr and base.

sizeof(id.type) may be part of nextwidth() or can be explicitly added.

addr is syntax tree node, base is the array address.

L → id [E]	a[i] in a[i][j][k]	{ L.type = id.type; L.addr = new Temp(); // ignore L.type.firstwidth() gen(L.addr '=' E.addr '*' L.type.nextwidth()); }

L → L_1 [E]	L[j] in a[i][j][k] then L[k]	{ L.type = L_1.type;
		t = new Temp();
		L.addr = new Temp();
		gen(t '=' E.addr '*' L.type.nextwidth());
		gen(L.addr '=' L_1.addr '+' t); }

E → id		{ E.addr = id.addr; }
E → L		{ E.addr = new Temp(); gen(E.addr '=' L.base '[' L.addr ']'); }
E → E_1 + E_2		{ E.addr = new Temp(); gen(E.addr '=' E_1.addr + E_2.addr); }
S → id = E		{ gen(id.name '=' E.addr); }
S → L = E		{ gen(L.base '[' L.addr ']' '=' E.addr); }

```
t1 = i * 12        ; 3 * 4 bytes
t2 = j * 4         ; 1 * 4 bytes
t3 = t1 + t2       ; offset from a
t4 = a[t3]         ; assuming base[offset] is present in IR.
t5 = c + t4
```

L → id [E]	{ L.type = id.type; L.addr = new Temp(); gen(L.addr '=' E.addr '*' L.type.width); }

L → L_1 [E]	{ L.type = L_1.type;
	t = new Temp();
	L.addr = new Temp();
	gen(t '=' E.addr '*' L.type.width);
	gen(L.addr '=' L_1.addr '+' t); }

E → id	{ E.addr = id.addr; }
E → L	{ E.addr = new Temp(); gen(E.addr '=' L.base '[' L.addr ']'); }
E → E_1 + E_2	{ E.addr = new Temp(); gen(E.addr '=' E_1.addr + E_2.addr); }
S → id = E	{ gen(id.name '=' E.addr); }
S → L = E	{ gen(L.base '[' L.addr ']' '=' E.addr); }

addr is syntax tree node,
base is the array address.

printMatrix

- What's wrong with this code?

```
int a[1][2], b[3][4], c[5][6];
...
printMatrix(a);
printMatrix(b);
printMatrix(c);
```

Second dimension is unknown.

```
int a[1][2], b[3][2], c[5][2];
...
printMatrix(a);
printMatrix(b);
printMatrix(c);
```

First dimension is unknown.

```
int a[1][2];
...
printMatrix(a);
```

Okay, the dimensions could be hard-coded by the programmer.

Type Qualifiers

- const: no assignment post initialization
  - via pointers?
- static: can be within a function or outside
  - Local: global lifetime, local scoping
  - Global: local to a file
- register: frequent use hinted by user
  - not recommended
- extern: defined in a different compilation unit
- volatile: disable memory optimizations
  - useful in multi-threaded programs

Language Constructs

to generate IR

- Declarations
  - Types (int, int [], struct, int *)
  - Storage qualifiers (array expressions, const, static)
- Assignments: LHS = RHS
- Conditionals, switch
- Loops
- Function calls, definitions

Control Flow

- Conditionals
  - if, if-else, switch
- Loops
  - for, while, do-while, repeat-until
- We need to worry about
  - Boolean expressions
  - Jumps (and labels)

Control-Flow – Boolean Expressions

- B → B || B | B && B | !B | (B) | E relop E | *true* | *false*
- relop → < | <= | > | >= | == | !=
- What is the associativity of ||?
- What is its precedence over &&?
- How to optimize evaluation of (B_1 || B_2) and (B_3 && B_4)?
  - Short-circuiting: *if (x < 10 && y < 20) ...*
  - **Classwork:** Write a C program to find out if C uses short-circuiting or not.
    - *while (p && p->next) ...*
    - *if (x || ++x) ...*
    - *x = (f() && g());*

Control-Flow – Boolean Expressions

- Source code:
  - if (x < 100 || x > 200 && x != y) x = 0;
- IR:

without short-circuit

```
    b1 = x < 100
    b2 = x > 200
    b3 = x != y
    iftrue b1 goto L2
    iffalse b2 goto L3
    iffalse b3 goto L3
L2:
    x = 0;
L3:
    ...
```

with short-circuit

```
    b1 = x < 100
    iftrue b1 goto L2
    b2 = x > 200
    iffalse b2 goto L3
    b3 = x != y
    iffalse b3 goto L3
L2:
    x = 0;
L3:
    ...
```

3AC for Boolean Expressions

$B \rightarrow B_1 \mid\mid B_2$

// attributes: true, false, code
// B_1.code, B_2.code are available.
// B.true, B.false are available (inherited attributes).

```
B1.true = B.true;
B1.false = newLabel();
B2.true = B.true;
B2.false = B.false;
B.code = B1.code +
           label(B1.false) +
           B2.code;
```

$B \rightarrow B_1$ && B_2

```
B1.true = newLabel();
B1.false = B.false;
B2.true = B.true;
B2.false = B.false;
B.code = B1.code +
           label(B1.true) +
           B2.code;
```

3AC for Boolean Expressions

B → !B$_1$

B_1.true = B.false;
B_1.false = B.true;
B.code = B_1.code;

B → E$_1$ **relop E**$_2$

B.code = E_1.code + E_2.code +
gen('if' E_1.addr *relop* E_2.addr
'goto' B.true) +
gen('goto' B.false);

B → true

B.code = gen('goto' B.true);

B → false

B.code = gen('goto' B.false);

SDD for *while*

$S \rightarrow$ while (C) S_1

// S.next, S_1.code
// C.true, C.false, C.code

```
L1       = newLabel();
L2       = newLabel();
S1.next  = L1;
C.false  = S.next;
C.true   = L2;
S.code   = "label" + L1 +
           C.code +
           "label" + L2 +
           S1.code +
           gen('goto' L1);
```

3AC for if / if-else

$S \rightarrow$ **if (B)** S_1

```
B.true = newLabel();
B.false = S₁.next = S.next;
S.code = B.code +
            label(B.true) +
            S₁.code;
```

$S \rightarrow$ **if (B)** S_1 **else** S_2

```
B.true = newLabel();
B.false = newLabel();
S₁.next = S₂.next = S.next;
S.code = B.code +
            label(B.true) + S₁.code +
            gen('goto' S.next) +
            label(B.false) + S₂.code;
```

Control-Flow – Boolean Expressions

- Source code: if (x < 100 || x > 200 && x != y) x = 0;

without optimization

```
    b1 = x < 100
    b2 = x > 200
    b3 = x != y
    iftrue b1 goto L2
    goto L0
L0:
    iftrue b2 goto L1
    goto L3
L1:
    iftrue b3 goto L2
    goto L3
L2:
    x = 0;
L3:
    ...
```

with short-circuit

```
    b1 = x < 100
    iftrue b1 goto L2
    b2 = x > 200
    iffalse b2 goto L3
    b3 = x != y
    iffalse b3 goto L3
L2:
    x = 0;
L3:
    ...
```

Avoids redundant gotos.

Homework

- Write SDD to generate 3AC for *for*.
  - *for (S1; B; S2) S3*
- Write SDD to generate 3AC for *repeat-until.*
  - *repeat S until B*

Backpatching

- *if (B) S* required us to pass label while evaluating B.
  - This can be done by using inherited attributes.
- Alternatively, we could leave the label unspecified now...
  - … and fill it in later.
- Backpatching is a general concept for one-pass code generation

B → true	B.code = gen('goto –');
B → B_1 || B_2	backpatch(B_1.false); ...

break and continue

- break and continue are disciplined / special gotos.
- Their IR needs
  - currently enclosing loop / switch.
  - goto to a label just outside / before the enclosing block.
- How to write the SDD to generate their 3AC?
  - either pass on the enclosing block and label as an inherited attribute, or
  - use backpatching to fill-in the label of goto.
  - Need additional restriction for *continue*.
- **Classwork**: How to support *break label*?

IR for switch

- Using nested if-else
- Using a table of pairs
  - <V_i, S_i>
- Using a hash-table
  - when i is large (say, > 10)
- Special case when V_is are consecutive integrals.
  - Indexed array is sufficient.

```
switch(E) {
    case V1: S1
    case V2: S2
    …
    case Vn-1: Sn-1
    default: Sn
}
```

Classwork: Write IR for switch (assume implicit break).

t = code for E
goto test
L_1: code for S1
goto next
L_2: code for S_2
goto next
…
L_{n-1}: code for S_{n-1}
goto next
L_n: code for S_n
goto next
test:
    if t = V_1 goto L_1
    if t = V_2 goto L_2
    …
    if t = V_{n-1} goto L_{n-1}
    goto L_n
next:

Sequence of statements,
Sequence of values

t = code for E
if t != V_1 goto L_1
code for S_1
goto next
L_1: if t != V_2 goto L_2
code for S_2
goto next
L_2:
…
L_{n-2}: if t != V_{n-1} goto L_{n-1}
code for S_{n-1}
goto next
L_{n-1}: code for S_n
next:

Sequence of
values and statements

switch(E) {
    case V_1: S_1
    case V_2: S_2
    …
    case V_{n-1}: S_{n-1}
    default: S_n
}

Functions

- Function definitions
  - Type checking / symbol table entry
  - Return type, argument types, void
  - Stack offset for variables
  - Stack offset for arguments
- Function calls
  - Push parameters
  - Switch scope / push environment
  - Jump to label for the function
  - Switch scope / pop environment
  - Pop parameters

Summary

- IR forms
  - 3AC, 2AC, 1AC
  - SSA
- IR generation
  - Types
  - Declarations
  - Assignments
  - Conditionals
  - Loops