编译原理
Complier Principles

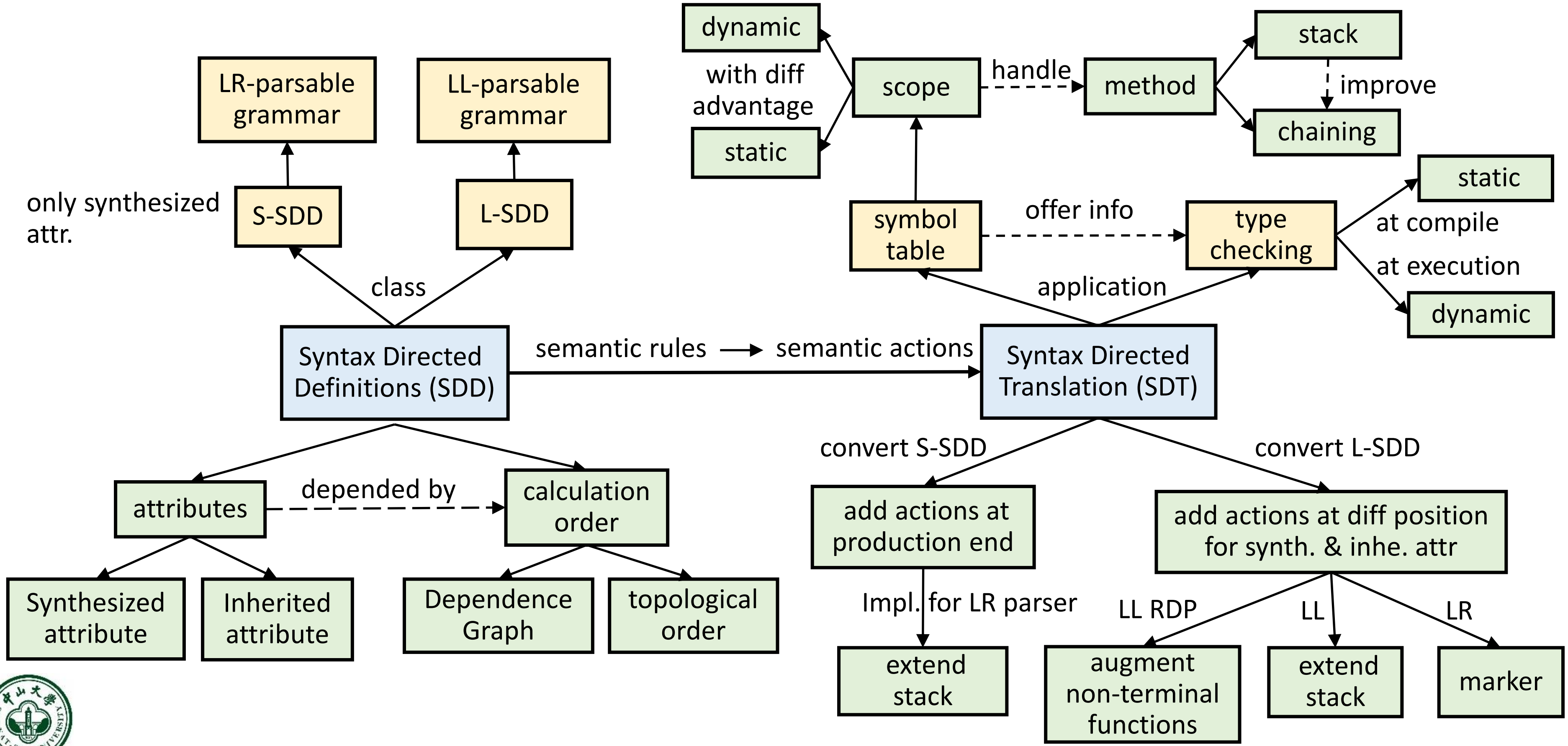
Lecture 8
Intermediate Code: Intro & IR

赵帅

计算机学院

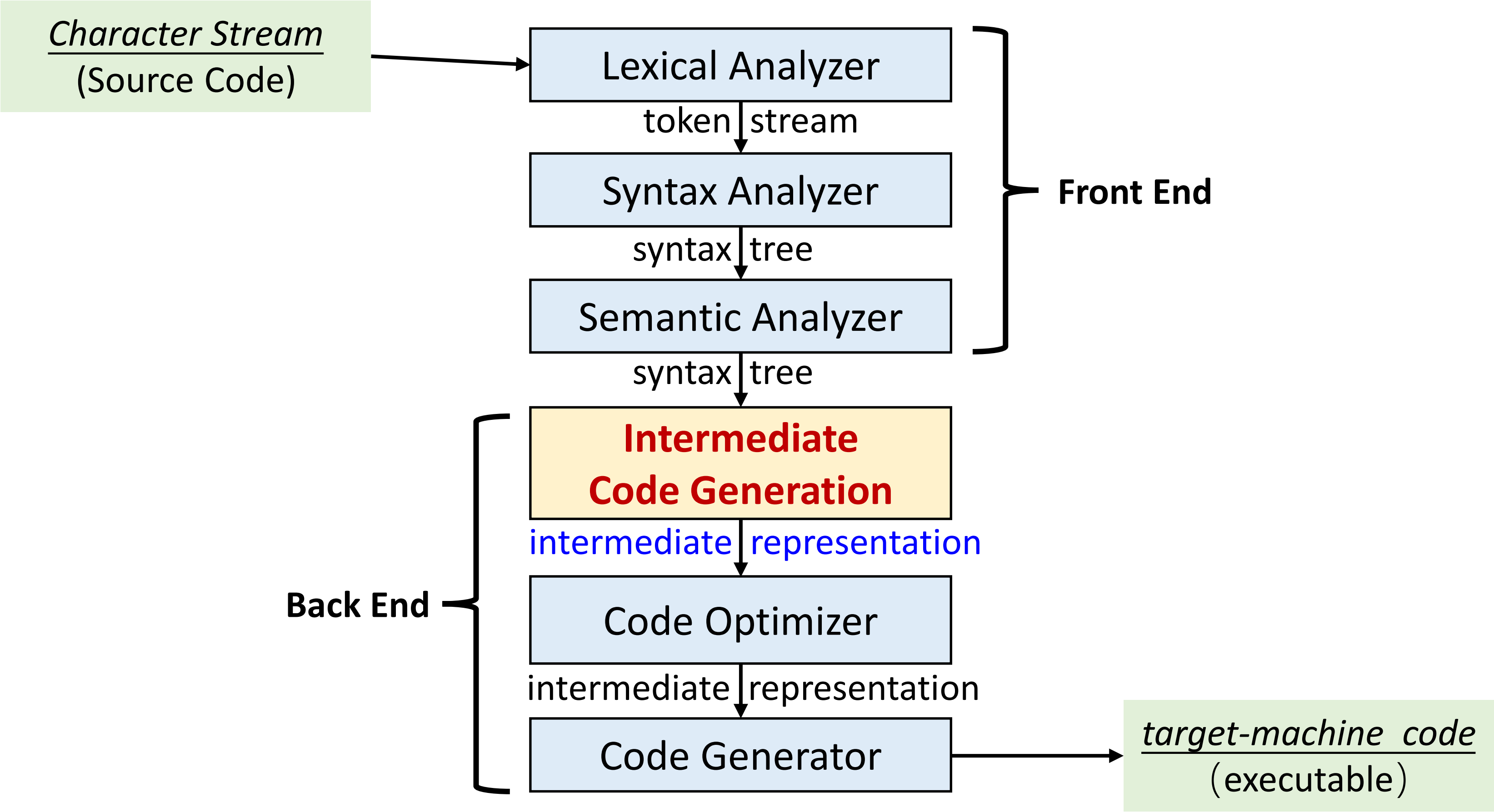
中山大学

Revisit

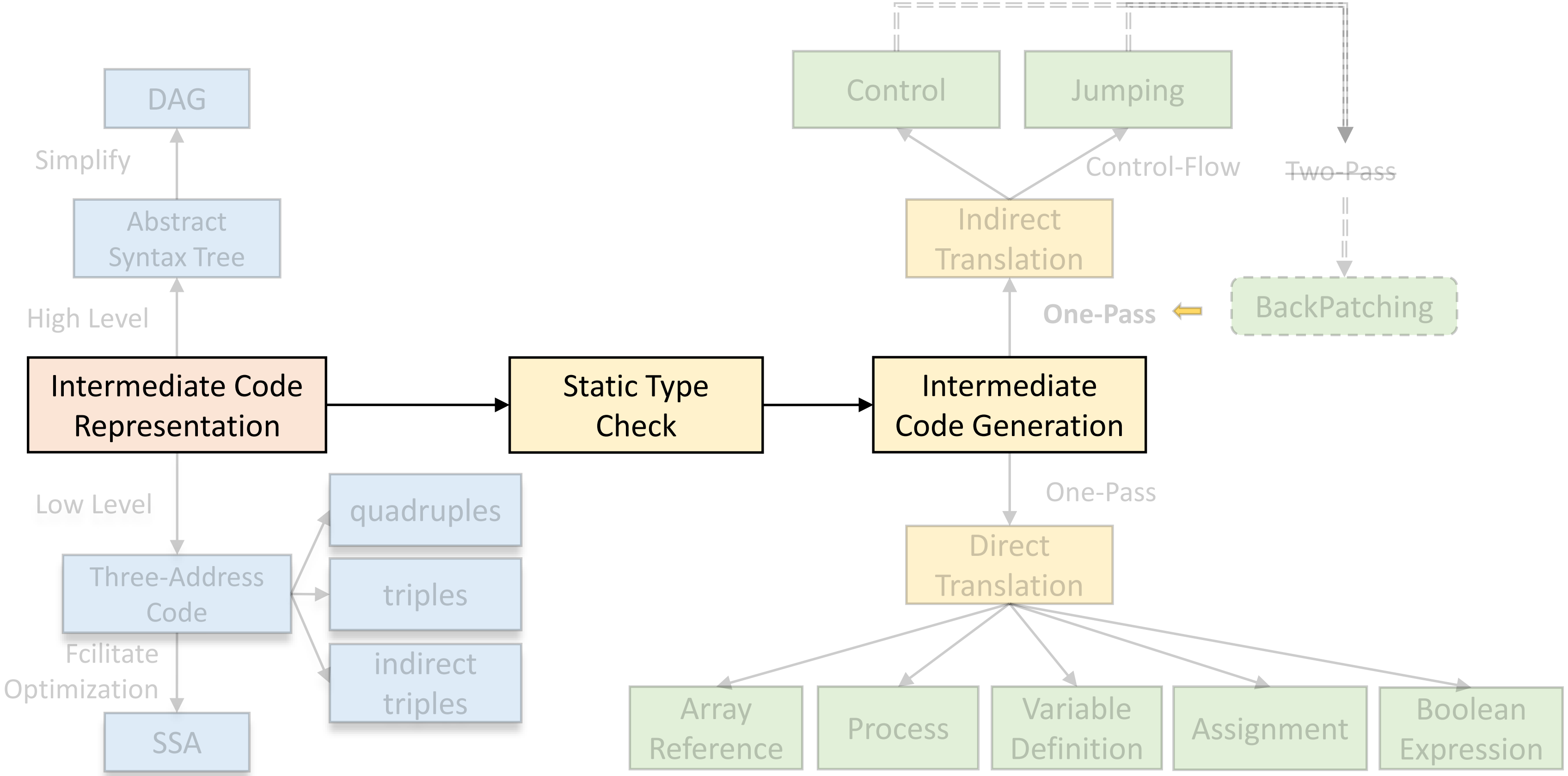


dynamic
with diff advantage
static
scope
handle
method
stack
improve
chaining
LR-parsable grammar
LL-parsable grammar
only synthesized attr.
S-SDD
L-SDD
symbol table
offer info
type checking
static
at compile
at execution
dynamic
class
application
Syntax Directed Definitions (SDD)
semantic rules → semantic actions
Syntax Directed Translation (SDT)
convert S-SDD
convert L-SDD
attributes
depended by
calculation order
add actions at production end
add actions at diff position for synth. & inhe. attr
Synthesized attribute
Inherited attribute
Dependence Graph
topological order
Impl. for LR parser
LL RDP
LL
LR
extend stack
augment non-terminal functions
extend stack
marker

Compilation Phases[编译阶段]



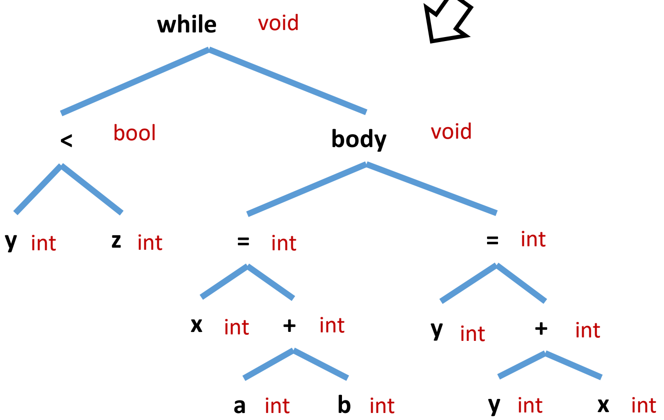
Intermediate Code[中间代码生成]



Compilation Phases[编译阶段]


```
while (y<z){
    int x = a + b;
    y += x;
}
```

(keyword, **while**)
(id, **y**)
(sym, **<**)
(id, **z**)
(id, **x**)
(id, **a**)
(sym, **+**)
(id, **b**)
(sym, **;**)
(id, **y**)
(sym, **+=**)
(id, **x**)
(sym, **;**)



Annotated AST/Decorated AST
[带标注的抽象语法树]

```
goto L1
L2:
        t1 := a + b
        x := t1
        t2 := y + x
        y := t2
L1:
        if y < z goto L2
```

Lexical Analyzer
token stream
Syntax Analyzer
syntax tree
Semantic Analyzer
syntax tree
Intermediate Code Generator
intermediate representation
Code Optimizer
intermediate representation
Code Generator
Target Machine Code

Multiple IR Levels [不同层级的中间表示]

- IR provides advantages [中间表示的优势]
  - ◆ Increased abstraction and cleaner separation
- A compiler may construct a sequence of intermediate representations.

Source Program → High-Level IR → … → Low-Level IR → Target Code

- Modern compilers use different IRs at different stages.
- **High-level IR** are close to *the source code* [接近源语言]
  - ◆ Example: Parse Tree, Abstract Syntax Tree [抽象语法树]
  - ◆ Language **dependent** (a high-level IR for each language)
  - ◆ Purpose: semantic analysis of program

Multiple Level IR[不同层级的中间表示]

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- **Low-level IR** are close to <u>*assembly*</u> [接近汇编]
  - E.g., three address code (TAC) [三地址码], static single assignment [静态单赋值]
  - Essentially an instruction set [指令集] for an abstract machine
  - Language and Machine **independent** (one common IR)
  - Purpose: compiler optimizations to make code efficient
    - All optimizations written in this IR is automatically applicable to all languages and machines
- **Machine-Level IR** [机器层级]
  - Example: x86 IR, ARM IR, …
  - Actual instructions for a concrete machine ISA [指令集架构]
  - Machine **dependent** (a machine-level IR for each ISA)
  - Purpose: code generation, CPU register allocation, etc

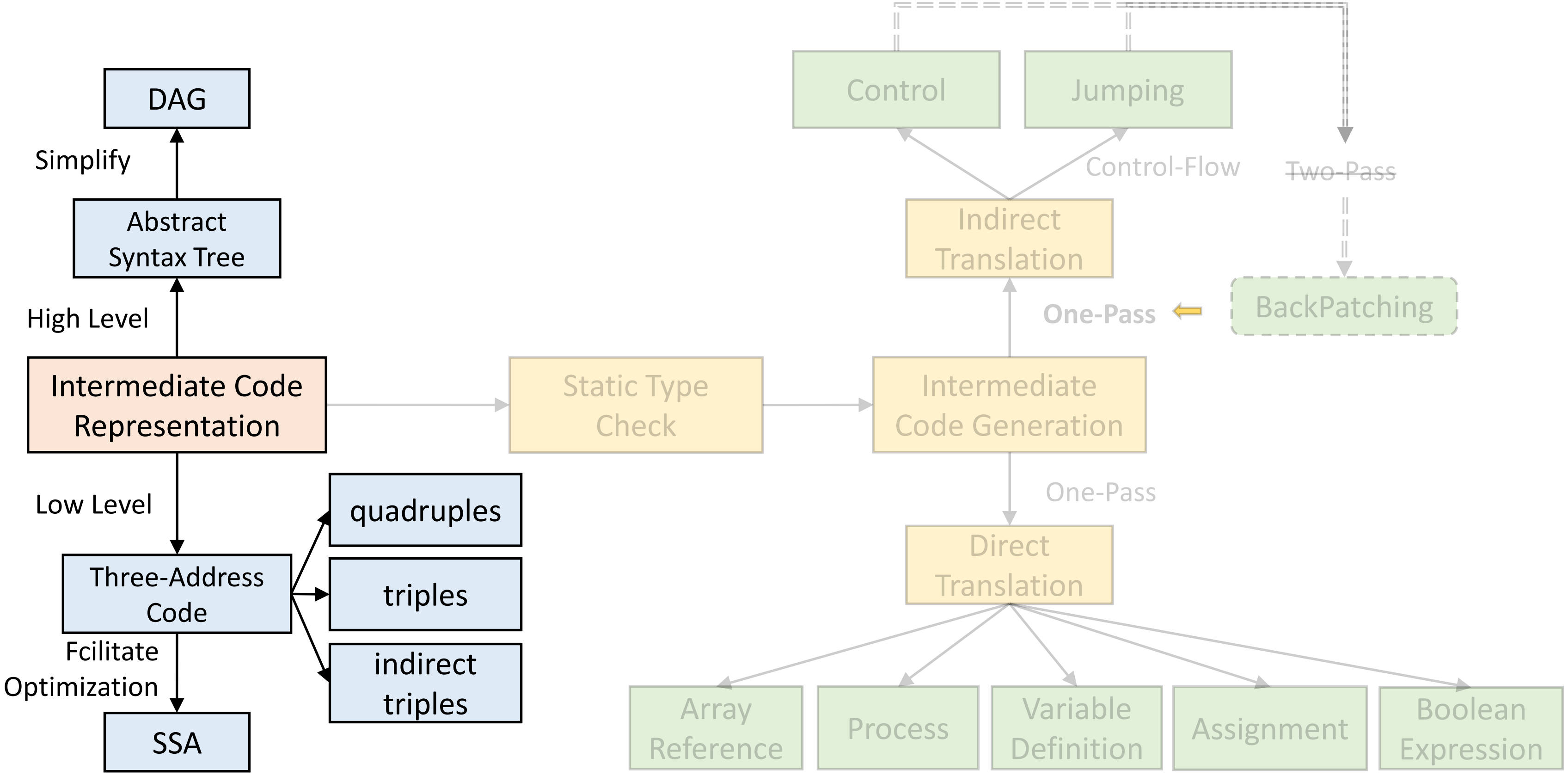
Multiple Level IR[不同层级的中间表示]

- Possible to have only one IR (AST) — some compilers follows this
  - ◆ Generate machine code from AST after semantic analysis [AST直接到机器码]
  - ◆ Makes sense *if compilation time is the primary concern* (e.g., JIT)
    - ▫ Skip the IR generation step
- Why multiple IRs?
  1. Better to have an appropriate IR for the task at hand [针对性]
     - ▫ *Semantic analysis* much easier with *high-level IR (AST)*
     - ▫ *Compiler optimizations* much easier with *low-level IR* (TAC)
     - ▫ *Register allocation* only possible with *machine-level IR* (ISA)

Multiple Level IR[不同层级的中间表示]

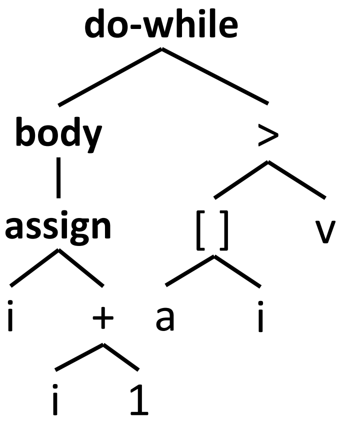
- Why multiple IRs?
  2. Easier to add a new front-end (language) or back-end (ISA) [易于扩展]
     - Front-end: a new AST → low-level IR converter
     - Back-end: a new low-level IR → machine IR converter
     - Low-level IR acts as a bridge between multiple front-ends and back-ends, such that they can be reused
- If one IR (AST), and adding a new front-end...
  - Reimplement all compiler optimizations for new AST
  - A new AST → machine code converter for each ISA
  - Same goes for adding a new back-end

Intermediate Code[中间代码生成]



Intermediate Representation[中间表示]

- **Two Most important IR:**
  - **Trees** [树形结构], including parse trees and (abstract) syntax trees [语法分析树和抽象语法树]
  - **Directed Acyclic Graph (DAG)** [有向无环图]
  - **Linear representations** [线性表示形式], especially "**three-address code**" [三地址代码]

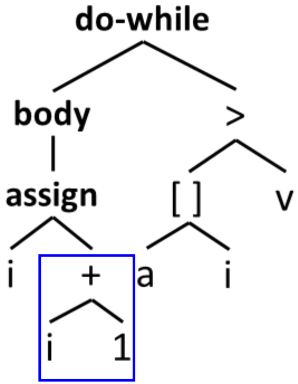


1: i = i + 1
2: t_1 = a [i]
3: if t_1 < v goto 1

Fig. Two forms of intermediate code for "do i=i+1; while(a[i]<v);"

Three-Address Code[三地址代码]

- At most one operator on the right side of an instruction in three-address code, e.g., **x + y *z** *translated into* **t_1 = y * z t_2 = x + t_1**
- Generic form is X = Y op Z [最多3个操作数]
  - where X, Y, Z can be *variables*, *constants*, or compiler-generated *temporaries* holding intermediate values.
- Characteristics [特性]
  - a linearized representation of *a syntax tree* or a *DAG*.
  - Assembly code for an “abstract machine”
  - Long expressions are converted to multiple instructions
  - Control flow statements are converted to jumps [控制流->跳转]
  - Machine independent

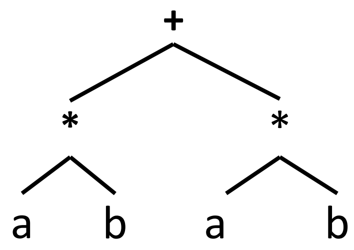


- Design goal: for easier machine-independent optimization

Three-Address Code[三地址代码]

- Example: a * b + a * b is translated to

$t_1 = a * b$
$t_2 = a * b$
$t_3 = t_1 + t_2$



  - t1, t2, t3 are temporary variables
  - Can be generated through a depth-first traversal of AST, and internal nodes in AST are translated to temporary variables

- The repetition of a * b can be eliminated by a compiler optimization called ***common subexpression elimination*** (CSE)[通用子表达式消除]

$t_1 = a * b$
$t_3 = t_1 + t_1$

- Using 3-address code rather than AST makes it:
  - Easier to spot optimization opportunities
  - Easier to manipulate IR.

Addresses in three-address code[地址]

- An address can be one of the following:
  - A name[名字]. For convenience, we allow source-program names to appear as address in three-address code.
  - A constant[常量]. In practice, a complier must deal with many different types of constants and variables.
  - A complier-generated temporary[编译器生成的临时变量]. Creating a distinct name each time a temporary is needed [在每次需要临时变量时产生一个新名字是必要的], especially in optimizing compliers.
    - These temporaries can be combined, if possible, when registers are allocated to variables.

Three-Address Instruction Form[三地址指令形式]

1. Assignment instructions [二元赋值]
   - x = y op z, op is a binary arithmetic[双目算术符] or logical operation [逻辑运算符]
2. Assignment instructions [一元赋值]
   - x = op y, where op is a unary operation[单目运算符]. Essential unary operations include *unary minus*, *logical negation*, *shift operators*, and *conversion operators*.
3. Copy instructions [复制]
   - x = y, where x is assigned the value of y [把y的值赋给x].
4. Unconditional Jump instructions [无条件转移指令]
   - goto L: the three-address instruction with label L is the next to be executed.
5. Conditional Jump instructions [条件转移指令]
   - if x goto L   if False x goto L   if (x relop y) goto L
   - where relop is a relational operator such as ==, >, <, etc.

Three-Address Instruction Form[三地址指令形式]

6. Procedure calls [程序调用]

- *param x* for parameters [参数传递];
- *call p,n* for procedure call – p: the procedure, n: the number of params.

param x_1
param x_2
…
param x_n
call p,n

param x1
param x2
param x3 call
foo, 3

- Part of a call of the procedure $p(x_1,x_2\ldots,x_n)$.

7. Procedure calls return statement [程序调用返回]

- return y, y representing a returned value, is optional.

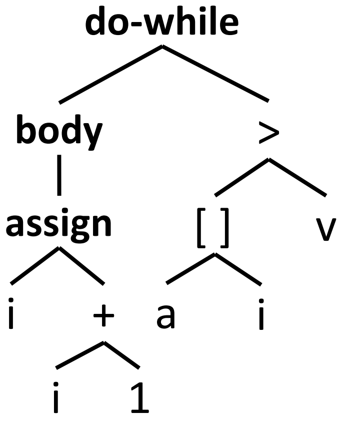
Three-Address Instruction Form[三地址指令形式]

8. Indexed copy instructions [带下标的复制指令]
   - ◆x = y[i]   x[i]=y
   - ◆x = y[i] sets *x* to the value in the location *i* memory units beyond location *y*.
   - ◆x[i]=y sets the contents of the location *i* units beyond *x* to the value of *y*.
9. Address and pointer assignments instructions. [地址及指针赋值指令]
   - ◆x = &y   *a pointer x is set to address of y* [取址]
   - ◆x = *y   *x is set to the value of location pointed to by pointer y* [y地址指向的值赋给x]
   - ◆*x = y   *location pointed to by x is assigned y* [y的值赋给x地址指向的位置]

Example

```
do {
    i = i + 1;
} while(a[i] < v)
```

Source program



Syntax tree

L: t_1 = i+1

   i = t_1

   t_2 = &a

   t_3 = sizeof(int)

   t_4 = t_3 * i

   t_5 = t_2 + t_4

   t_6 = *t_5

   if t_6 < v goto L

a[i]

Three-address code

Implementation of Three-address Code[实现]

- Three representations. (and more)
  - **quadruples.** [四元式]
  - **triples.** [三元式]
  - **indirect triples.** [间接三元式]
- Trade-offs between space, speed, ease of manipulation.
- **Quadruples.** [四元式]
  - A quadruple has four fields, which we call op, arg_1, arg_2, result.
  - Examples & some exceptions:
    - x = y + z => (+, y, z, x)
    - Note that for a copy statement like **x = y**, **op is =**, while for most other operations, the assignment operator is implied. [隐含表示的]

Quadruples[四元式]

- **Quadruples.** [四元式]
  - Examples & some exceptions:
    - x = `minus` y => (`minus`, y, , x)
      - Instructions with unary[一元] operators like x = `minus` y or x = y do not use arg_2.
    - Operators like `param` use neither arg_2 nor result.
      - (param, x1, ,)
    - goto L => (goto, , , L)
      - Conditional and Unconditional jumps put the target label in result. [条件或非条件转移指令将目标标号放入result字段]

Quadruples[四元式]

- **Example:** $a = b * (-c) + b * (-c)$
  - The special operator `minus` is used to distinguish the unary minus operator, as in "-c", from the binary minus operator, as in "b-c".

t_1 = minus c

$t_2 = b * t_1$

t_3 = minus c

$t_4 = b * t_3$

$t_5 = t_2 + t_4$

$a = t_5$

Three-address code

	op	arg_1	arg_2	result
(0)	minus	c		t_1
(1)	*	b	t_1	t_2
(2)	minus	c		t_3
(3)	*	b	t_3	t_4
(4)	+	t_2	t_4	t_5
(5)	=	t_5		a

Quadruples

Triples[三元式]

- A triple has only three fields, which we call op, arg_1, arg_2.
  - Quadruple without the result field.
    - x = y + z => (+, y, z)
    - the assignment operator (x=) is implied
  - Result field is implicitly index of instruction.
  - Result referred to by index of instructions computing it.
    - See example in the next slide

Triples[三元式]

- **Example:** $a = b * (-c) + b * (-c)$
  - The copy statement $a=t_5$ is encoded in the triple representation by placing *a* in the arg_1 field and (4) in the arg_2 field.

	op	**arg_1**	**arg_2**	**result**
(0)	minus	c		t_1
(1)	*	b	t_1	t_2
(2)	minus	c		t_3
(3)	*	b	t_3	t_4
(4)	+	t_2	t_4	t_5
(5)	=	t_5		a

Quadruples

	op	**arg_1**	**arg_2**
(0)	minus	c	
(1)	*	b	(0)
(2)	minus	c	
(3)	*	b	(2)
(4)	+	(1)	(3)
(5)	=	a	(4)

Triples

More About Triples[三元式]

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- How can the following statements be expressed in triple?
  - Array location (e.g. x[i] = y)
  - Pointer location (e.g. *(x+i) = y)
  - Struct field location (e.g. x.i = y)
- Example: x[i] = y
  - Requires two entries in the triple structure.
  - is translated to:

	op	arg_1	arg_2
(0)	[]	x	i
(1)	=	(0)	y

Complex LHS may require more triples to compute address

// Compute address of x[i] location

// Assign y to that location

Problems About Triples[三元式]

- Problem with triples
  - In code optimization, *instructions are often moved around*.
  - With triples, the result of an operation is referred to by its position, so moving an instruction may require us to change all references to that result.

	op	arg_1	arg_2	result
(0)	minus	c		t_1
(1)	*	b	t_1	t_2
(2)	minus	c		t_3
(3)	*	b	t_3	t_4
~~(4)~~ (2)	+	t_2	~~t_4~~ t_2	t_5
~~(5)~~ (3)	=	t_5		a

	op	arg_1	arg_2
(0)	minus	c	
(1)	*	b	(0)
(2)	minus	c	
(3)	*	b	(2)
~~(4)~~ (2)	+	(1)	~~(3)~~ (1)
~~(5)~~ (3)	=	a	(4)

$t_1 = a * b$

~~$t_2 = a * b$~~

$t_3 = t_1 + t_2$

$t_1 = a * b$

$t_3 = t_1 + t_1$

CSE

Problems About Triples[三元式]

- Problem with triples
  - ◆ In code optimization, *instructions are often moved around*.
  - ◆ With triples, the result of an operation is referred to by its position, so moving an instruction may require us to change all references to that result.

	op	arg_1	arg_2	result
(0)	minus	c		t_1
(1)	*	b	t_1	t_2
(2)	+	t_2	t_2	T_5
(3)	=	t_5		a

	op	arg_1	arg_2
(0)	minus	c	
(1)	*	b	(0)
(2)	+	(1)	(1)
(3)	=	a	**(4)**

Instruction (3) refers to (4) which is no longer there.

Three-Address Code[三地址代码] (Recap)

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- Generic form is X = Y op Z [最多3个操作数]
- Three representations. (and more)
  - **quadruples** [四元式]
    - x = y + z => (+, y, z, x)
  - **triples** [三元式]
    - x = y + z => (1) (+, y, z), use index for the result
  - **indirect triples** [间接三元式]
    - use an index list for TAC execution

step	*instruction*
0	(0)
1	(1)
2	(2)
3	(0)
4	(3)
5	(4)

a triple 'database'

index	**op**	**arg_1**	**arg_2**
(0)	+	a	b
(1)	*	(0)	c
(2)	=	x	(1)
(3)	/	d	(0)
(4)	=	y	(3)

- Single Static Assignment
  - Every variable is assigned exactly once statically[仅一次]

Indirect Triples[间接三元式]

- *The problem does not occur with **indirect triples.***
- Indirect triples consist of a listing of pointers to triples, rather than a listing of triples themselves.

step	*instruction*
0	(0)
1	(1)
2	(2)
3	(3)
4	(4)
5	(5)

Triples are stored in a triple 'database'

index	**op**	**arg_1**	**arg_2**
(0)	minus	c	
(1)	*	b	(0)
(2)	minus	c	
(3)	*	b	(2)
(4)	+	(1)	(3)
(5)	=	a	(4)

Indirect Triples[间接三元式]

- After CSE, empty entries in database can be reused
  - Code in triple database becomes non-contiguous over time
  - That's fine since the listing is the code, not the database

Triples are stored in a triple 'database'

step	*instruction*
0	(0)
1	(1)
2	(4)
3	(5)

index	op	arg_1	arg_2
(0)	minus	c	
(1)	*	b	(0)
(2)		empty	
(3)		empty	
(4)	+	(1)	(1)
(5)	=	a	(4)

Indirect Triples[间接三元式]

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- Another Example: x = (a+b)*c; y = d/(a+b)

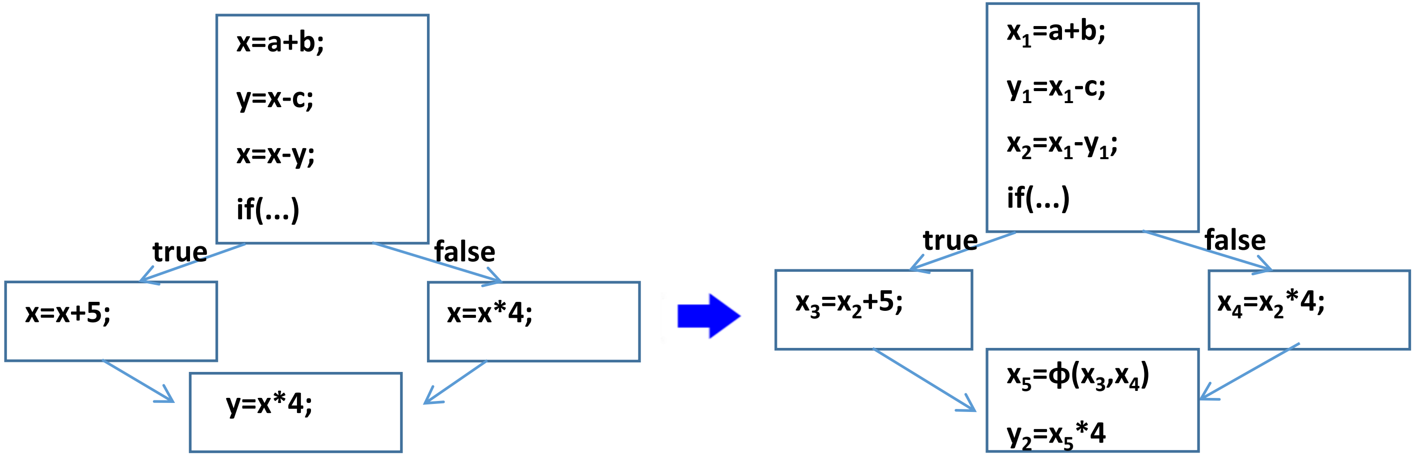
step	*instruction*
0	(0)
1	(1)
2	(2)
3	(0)
4	(3)
5	(4)

index	**op**	**arg$_1$**	**arg$_2$**
(0)	+	a	b
(1)	*	(0)	c
(2)	=	x	(1)
(3)	/	d	(0)
(4)	=	y	(3)

- With indirect triples, an optimizing complier can move an instruction by reordering the instruction list, without affecting the triples themselves.

Single Static Assignment[静态单赋值]

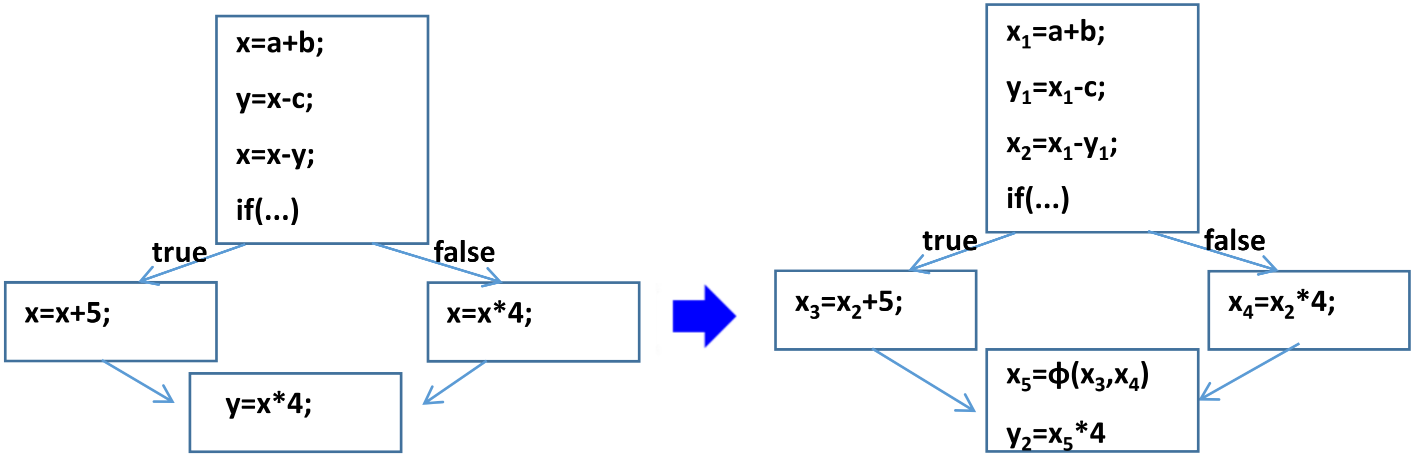
- Every variable is assigned exactly once statically[仅一次]
  - Give variable a different version name on every assignment
    - e.g. $x \rightarrow x_1, x_2, \ldots, x_5$ for each static assignment of x
  - Now value of each variable guaranteed not to change
  - On a control flow merge, ϕ-function combines two versions
    - e.g. $x_5 = \phi(x_3, x_4)$: means x_5 is either x_3 or x_4



Benefits of SSA

- **SSA** is an IR that facilitates code optimization
  - SSA tells you when an optimization **should not** happen
  - Suppose compiler performs CSE on previous example:
    - Without SSA, (incorrectly) tempted to eliminate second x * 4

      x = x * 4;   y = x * 4;   →   x = x * 4;   y = x;
    - With SSA, x_2 * 4 and x_5 * 4 are clearly different values



Benefits of SSA (cont.)

- SSA is an IR that facilitates code optimizations
  - SSA tells you when an optimization **should** happen
  - Suppose compiler performs **dead code elimination** (DCE): (DCE removes code that computes dead values)
  - Without SSA, not very clear whether there are dead values
  - With SSA, x1 is never used and clearly a dead value

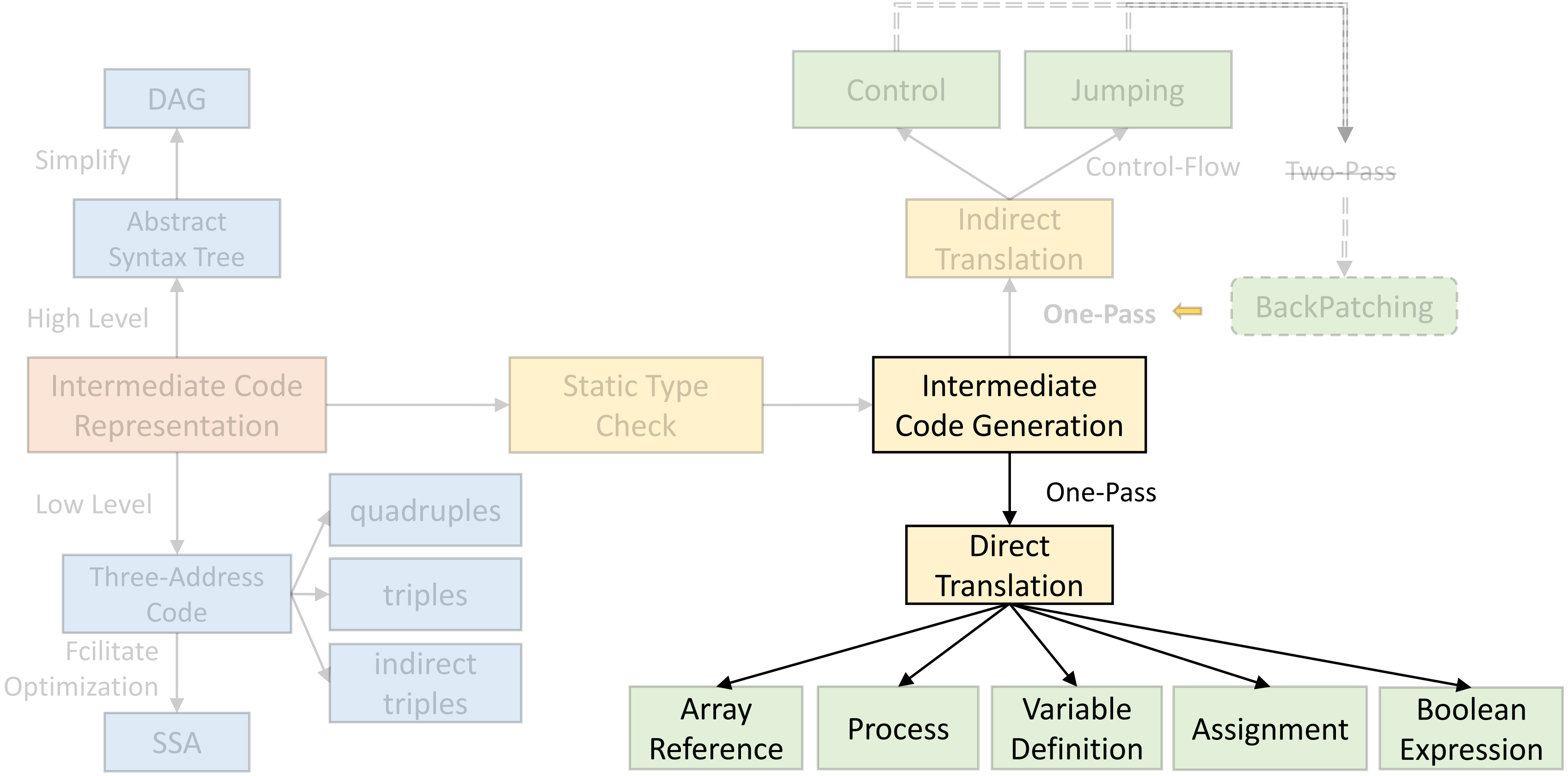
$x = a + b;$ $x = c - d;$ $y = x * b;$	⇨	$x_1 = a + b;$ $x_2 = c - d;$ $y_1 = x_2 * b;$

- Why does SSA work so well with compiler optimizations?
  - SSA makes flow of values explicit in the IR
  - Without SSA, need a separate dataflow graph
  - Will discuss more in **Compiler Optimization** section

Syntax Directed Translation[语法制导翻译]

- Syntax directed translation can be used again for code generation [代码生成]
  - ◆ Code generation is dependent on syntax/AST
  - ◆ Code generation is to translate the syntactic structures
- What language structures do we need to translate?[翻译]
  - ◆ Definitions (variables, functions, ...)
  - ◆ Assignment statements
  - ◆ Array references
  - ◆ Boolean expressions
  - ◆ Control flow statements (if-then-else, for, etc)...
- We are going to use the following strategy:
  - ◆ Specify SDD semantic rules (without ordering)
  - ◆ Convert SDD rules to SDT actions (with ordering)

Intermediate Code[中间代码生成]



Code Generation Overview[代码生成]

- Program code is a collection of functions
  - By now, all functions are listed in symbol table
- Goal is to generate code for each function in that list
- Generating code for a function involves two steps:
  - Processing variable definitions[变量定义] -> Laying out variables in memory
  - Processing statements[语句] -> Generating instructions for statements
    - Assignments, array references, boolean expressions, control-flow statements
- We will start with **variable definitions**

Processing Variable Definitions[变量定义]

- To lay out a variable, both location and width are needed
  - Location: where variable is located in memory
  - Width: how much space variable takes up in memory
- Attributes for variable definition:
  - **T V**, e.g., int x;
  - **T**: non-terminal for type name
    - **T.type**: type (int, float, ...)
    - **T.width**: width of type in bytes (e.g., 4 for int)
  - **V**: non-terminal for variable name
    - **V.type**: type (int, float, ...)
    - **V.width**: width of variable according to type
    - **V.offset**: offset of variable in memory
  - But offset from what...?

Variable Location from Offset

- Naive method: reserve a big memory section for all data
  - Size data section to be large enough to contain all variables
  - Location = var offset + base of data section
- Naive method wastes a lot of memory
  - Vars with limited scope only live briefly in memory
    - E.g., function variables last only for duration of call
- **Solution**: allocate memory for each scope[域内]
  - Allocate when entering scope, free when exiting scope
  - Variables in the same scope are allocated / freed together
  - Location = var offset + base of scope memory section
  - Will discuss more later in **Runtime Management**

Storage Layout of Variables in a Function

- When there are multiple variables defined in a function
  - Compiler lays out variables in memory sequentially
  - Current offset used to place variable x in memory
    - address(x) ← offset
    - offset += sizeof(x.type)

```
void foo() {
    int a;
    int b;
    long long c;
    int d;
}
```

Address		
0x0000	a	Offset = 0 Addr(a) ← 0
0x0004	b	Offset = 4 Addr(b) ← 4
0x0008	c	Offset = 8 Addr(c) ← 8
0x000c	c	
0x0010	d	Offset = 16 Addr(d) ← 16
		Offset = 20

More about Storage Layout

- Allocation alignment[对齐]
  - Enforce addr(x) % sizeof(x.type) == 0
  - Most machine architectures are designed such that computation is most efficient at sizeof(x.type) boundaries
    - E.g. most machines are designed to load integer values at integer word boundaries
    - If not on word boundary, need to load two words with shift & concatenate → inefficient

```
void foo() {
    char a;         // addr(a) = 0
    int b;          // addr(b) = 1
    int c;          // addr(c) = 5
    long long d;    // addr(d) = 9
}
```

➡

```
void foo() {
    char a;         // addr(a) = 0
    int b;          // addr(b) = 4
    int c;          // addr(c) = 8
    long long d;    // addr(d) = 16
}
```

```
#include<stdio.h>

struct{
   char x; int y;
}Test;

int main() {
   printf("%d\n",sizeof(Test));
   return 0;
}
```

What is the output?

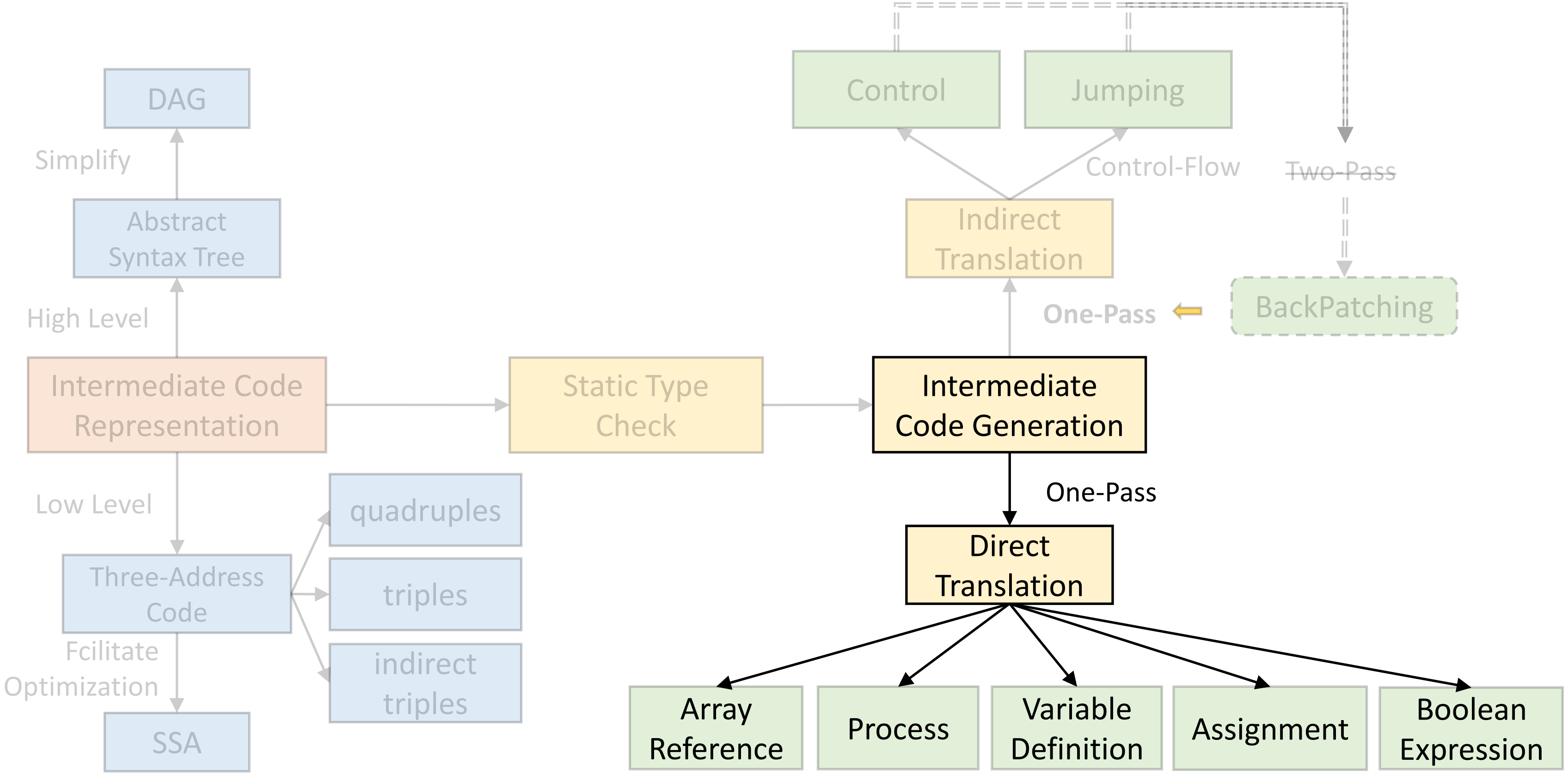
Not aligned: 5, Aligned: 8

Code Generation[代码生成]

- We will use the syntax-directed formalisms to specify translation
  - Variable definitions[变量定义] -> Recall semantic analysis & symbol table
  - Assignment[赋值]
  - Array references[数组引用]
  - Boolean expressions[布尔表达式]
  - Control-flow statements[控制流语句]

- To generate three-address codes (TACs)
  - Lay out variables in memory
  - Generate TAC for any subexpressions or substatements
  - Using the result, generate TAC for the overall expression

Intermediate Code[中间代码生成]



Code Generation[代码生成]

- SSA (Single Static Assignment)
- We will use the syntax-directed formalisms to specify translation
  - ◆ Variable definitions[变量定义] -> Recall semantic analysis & symbol table
  - ◆ Assignment[赋值]
  - ◆ Array references[数组引用]
  - ◆ Boolean expressions[布尔表达式]
  - ◆ Control-flow statements[控制流语句]
- To generate three-address codes (TACs)
  - ◆ Lay out variables in memory
  - ◆ Generate TAC for any subexpressions or substatements
  - ◆ Using the result, generate TAC for the overall expression

CodeGen: Assignment Statement

- Translate into three-address code[赋值语句]
  - An expression with more than one operator will be translated into instructions with at most one operator per instruction
- Helper functions in translation
  - lookup(id): search id in symbol table, return null if none
  - emit()/gen(): generate three-address IR
  - newtemp(): get a new temporary location

①S -> id = E;

② E -> E_1 + E_2;

③ E -> - E_1

④ E -> (E_1)

⑤ E -> id

Assignment statement:

a = b + (-c)

Three-address code:

t_1 = minus c

t_2 = b + t_1

a = t_2

SDT Translation of Assignment

- Attributes code and addr
  - S.code and E.code denote the TAC for S and E, respectively
  - E.addr denotes the address that will hold the value of E (can be a name, constant, or a compiler-generated temporary)

Assignment statement:

a = b + (-c)

Three-address code:

t_1 = minus c

t_2 = b + t_1

a = t_2

① S -> id = E;

② E -> E_1 + E_2;

③ E -> - E_1

④ E -> (E_1)

⑤ E -> id

① S -> id = E; { p = lookup(id.lexeme); if !p then error; S.code = E.code || gen(p '=' E.addr); }

② E -> E1 + E2; { E.addr = newtemp(); E.code = E1.code || E2.code ||gen(E.addr '=' E1.addr '+' E2.addr); }

③ E -> - E1 { E.addr = newtemp(); E.code = E1.code || gen(E.addr '=' 'minus' E1.addr); }

④ E -> (E1) { E.addr = E1.addr; E.code = E1.code; }

⑤ E -> id { E.addr = lookup(id.lexeme); if !E.addr then error; E.code = ''; }

Incremental Translation[增量翻译]

- Generate only the new three-address instructions
  - gen() not only constructs a three-address inst, it appends the inst to the sequence of insts generated so far

① S -> id = E;

② E -> E_1 + E_2;

③ E -> - E_1

④ E -> (E_1)

⑤ E -> id

S -> id = E; { p = lookup(id.lexeme); if !p then error; S.code = E.code || gen(p '=' E.addr); }

② E -> E1 + E2; { E.addr = newtemp(); E.code = E1.code || E2.code || gen(E.addr '=' E1.addr '+' E2.addr); }

③ E -> - E1 { E.addr = newtemp(); E.code = E1.code || gen(E.addr '=' 'minus' E1.addr); }

④ E -> (E1) { E.addr = E1.addr; E.code = E1.code; }

⑤ E -> id { E.addr = lookup(id.lexeme); if !E.addr then error; E.code = ''; }

Code Generation[代码生成]

- We will use the syntax-directed formalisms to specify translation
  - Variable definitions[变量定义] -> Recall semantic analysis & symbol table
  - Assignment[赋值]
  - Array references[数组引用]
  - Boolean expressions[布尔表达式]
  - Control-flow statements[控制流语句]

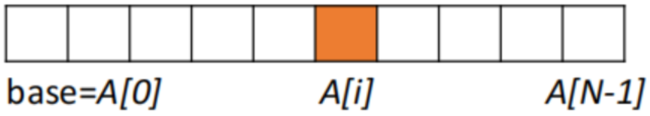
- To generate three-address codes (TACs)
  - Lay out variables in memory
  - Generate TAC for any subexpressions or substatements
  - Using the result, generate TAC for the overall expression

CodeGen: Array Reference[数组引用]

- Primary problem in generating code for array references is to determine the address of element
- 1D array:

  int A[N];

  A[i] ++;



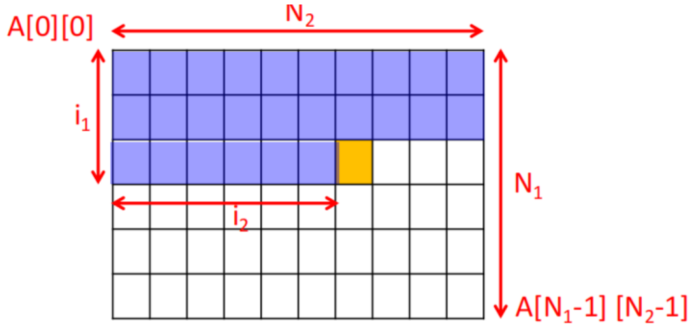
  - base: address of the first element
  - width: width of each element
    - i * width is the offset
- Addressing an array element
  - addr(A[i]) = base + i × width

N-dimensional Array

- Laying out 2D array in 1D memory

  $int\ A[N_1][N_2];$ /* int A[0..N_1][0..N_2] */

  $A[i_1][i_2]$ ++;



- Organization by row-major or column-major
  - C language uses row major (i.e., row by row)
  - $addr(A[i_1, i_2]) = base + (i_1 \times \underbrace{N_2 * width}_{W_1} + i_2 \times \underbrace{width}_{W_2})$

    第i_1行　第i_2列

    N_2：列数
- k-dimensional array
  - $addr(A[i_1][i_2]...[i_k]) = base + i_1 \times W_1 + i_2 \times W_2 + ... + i_k \times W_k$

Translation of Array References

- Type(a) = array(10, int)
  - ◆ c = a[i];

addr(a[i]) = base + i*4

t_1 = i * 4

t_2 = a[t_1]

c = t_2

3行5列

- Type(a) = array(3, array(5, int))
  - ◆ c = a[i_1][i_2];

addr(A[i_1 ,i_2]) = base + (i_1 × N_2*width + i_2 × width)

addr(a[i_1][i_2]) = base + i_1*20 + i_2*4

t_1 = i_1 * 20

t_2 = i_2 * 4

t_3 = t_1 + t_2

t_4 = a[t_3]

c = t_4

3个5行8列

- Type(a) = array(3, array(5, array(8, int)))
  - ◆ c = a[i_1][i_2][i_3]

addr(a[i_1][i_2][i_3]) = base + i_1*w_1 + i_2*w_2 + i_3*w_3

= base + i_1*160 + i_2*32 + i_3*4

160: a complete 2D array

Translation of Array References (cont.)

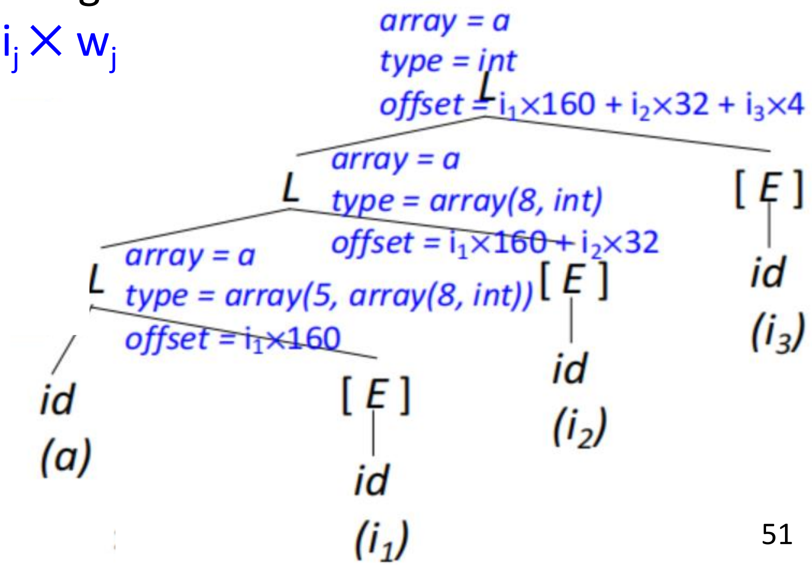
- A[i1][i2][i3], type(a) = array(3, array(5, array(8, int)))
  - L.array: a pointer to the symbol-table entry for the array name
    - L.array.base gives the array's base address
  - L.type: the type of the subarray generated by L
  - L.addr: a temporary that is used while computing the offset for the array referenced by summing the terms $i_j \times w_j$

① S -> id = E; | L = E;

② E -> $E_1 + E_2$ | - E_1 | (E_1) | id | L

③ L -> id [E] | L_1 [E]

$base + i_1 \times w_1 + i_2 \times w_2 + \ldots + i_k \times w_k$



Translation of Array References (cont.)

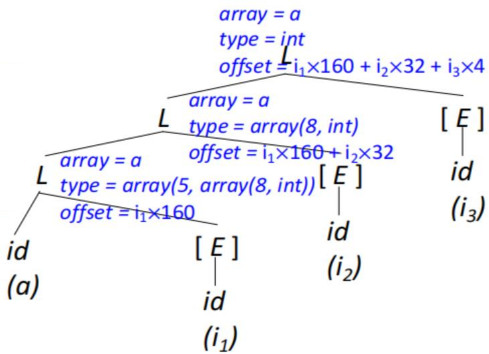
- A[i1][i2][i3], type(a) = array(3, array(5, array(8, int)))

① S -> id = E; | L = E; { gen(L.array.base‘[’L.addr‘]’ ‘=’ E.addr); }

② E -> E1 + E2 | - E1 | (E1) | id | L { E.addr = newtemp(); gen(E.addr ‘=’ L.array.base‘[’L.addr‘]’); }

③ L -> L1 [E] { L.array = L1.array; L.type = L1.type.elem; t = newtemp(); gen(t ‘=’ E.addr ‘*’ L.type.width); L.addr = newtemp(); gen(L.addr ‘=’ L1.addr ‘+’ t; } |

id [E] { L.array = lookup(id.lexeme); if !L.array then error; L.type = L.array.type.elem; L.offset = newtemp(); gen(L.addr ‘=’ E.addr ‘*’ L.type.width); }



$t_1 = i_1 * 160$ $\quad$ $t_4 = i_3 * 4$

$t_2 = i_2 * 32$ $\quad$ $t_5 = t_3 + t4$

$t_3 = t_1 + t2$ $\quad$ $c = a[t_5]$

Code Generation[代码生成]

- We will use the syntax-directed formalisms to specify translation
  - Variable definitions[变量定义] -> Recall semantic analysis & symbol table
  - Assignment[赋值]
  - Array references[数组引用]
  - Boolean expressions[布尔表达式]
  - Control-flow statements[控制流语句]

- To generate three-address codes (TACs)
  - Lay out variables in memory
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  - Using the result, generate TAC for the overall expression

CodeGen: Boolean Expressions

- Boolean expression: a op b
  - where op can be <, <=, !=, >, >=, &&, ||, ==, …
- Short-circuit evaluation[短路计算]: to skip evaluation of the rest of a boolean expression once a boolean value is known
  - Given following C code: `if (flag || foo()) { bar(); };`
    - If flag is true, foo() never executes
    - Equivalent to: `if (flag) { bar(); } else if (foo()) { bar(); };`
  - Given following C code: `if (flag && foo()) { bar(); };`
    - If flag is false, foo() never executes
    - Equivalent to: `if (!flag) { } else if (foo()) { bar(); };`
- For control flow, boolean operators is translated to jump statements

Boolean Expressions

- Computed just like any other arithmetic expression

$E \rightarrow (a < b)\ or\ (c < d\ and\ e < f)$

$t_1 = a < b$

$t_2 = c < d$

$t_3 = e < f$

$t_4 = t_2\ \&\&\ t_3$

$t_5 = t_1\ ||\ t_4$

- Then, used in control-flow statements
  - S.next: label for code generated after S

$S \rightarrow if\ E\ S_1$

$if\ (!t_5)\ goto\ S.next$

$S_1.code$

$S.next: ...$

Boolean Expressions

- Implemented via a series of jumps[利用跳转]
  - converted to two gotos (true and false)
  - Remaining evaluation skipped when result known in middle
- Example
  - E.true: label for code to execute when E is ‘true’
  - E.false: label for code to execute when E is ‘false’
  - E.g. if above is condition for a do-while loop
    - E.true would be label at beginning of loop body
    - E.false would be label for code after the loop

E -> (a < b) or (c < d and e < f)

if (a < b) goto E.true

goto L_1

L_1*: if (c < d) goto* L_2

goto E.false

L_2*: if (e < f) goto E.true*

goto E.false

E为真：只要a < b真

a < b假：继续评估

a < b假、 c < d真：继续评估

E为假：a < b假，c < d假

E为真：a < b假，c < d真，e < f真

E为假：a < b假，c < d真，e < f假

Boolean Expressions

- Boolean expressions are composed of
  - Boolean operators (==, &&, ||) applied to elements that are boolean variables or relational expressions (E1 relop E2)
- Computed just like any other arithmetic expression

E -> (a < b) or (c < d and e < f)

$t_1 = a < b$

$t_2 = c < d$

$t_3 = e < f$

$t_4 = t_2 \ \&\& \ t_3$

$t_5 = t_1 \ || \ t_4$

- Then, used in control-flow statements
  - S.next: label for code generated after S

S -> if E S_1

if (!t_5*) goto S.next*

S_1*.code*

S.next: ...

SDT Translation of Booleans[布尔表达式]

- B -> B1 || B2
  - B1.true is same as B.true, B2 must be evaluated if B1 is false[B1假才评估B2]
  - The true and false exits of B2 are the same as B[B2与B同真假]
- B -> E1 relop E2
  - Translated directly into a comparison TAC inst with jumps

① B -> { B_1.true = B.true; B_1.false = newlabel(); } B_1 || { label(B_1.false); B_2.true = B.true; B_2.false = B.false; } B_2

② B -> { B_1.true = newlabel(); B_1.false = B.false; } B_1 && { label(B_1.true); B_2.true = B.true; B_2.false = B.false; } B_2

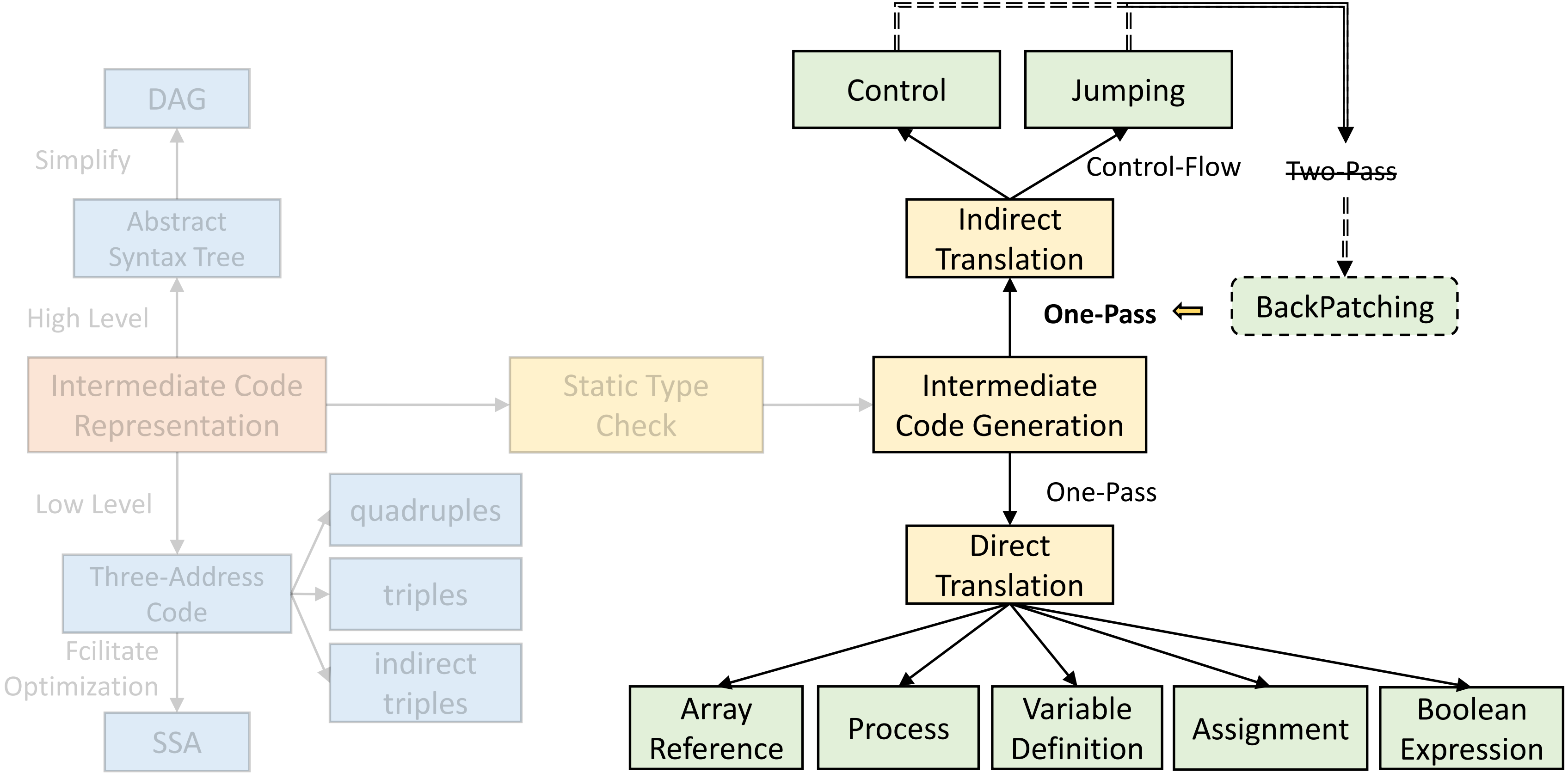
③ B -> E_1 relop E_2 { gen('if' E_1.addr relop E_2.addr 'goto' B.true); gen('goto' B.false; }

④ B -> ! { B_1.true = B.false; B_1.false = B.true; } B_1

⑤ B -> true { gen('goto' B.true; }

⑥ B -> false { gen('goto' B.false; }

Intermediate Code[中间代码生成]



Code Generation[代码生成]

- We will use the syntax-directed formalisms to specify translation
  - ◆ Variable definitions[变量定义] -> Recall semantic analysis & symbol table
  - ◆ Assignment[赋值]
  - ◆ Array references[数组引用]
  - ◆ Boolean expressions[布尔表达式]
  - ◆ Control-flow statements[控制流语句]

- To generate three-address codes (TACs)
  - ◆ Lay out variables in memory
  - ◆ Generate TAC for any subexpressions or substatements
  - ◆ Using the result, generate TAC for the overall expression

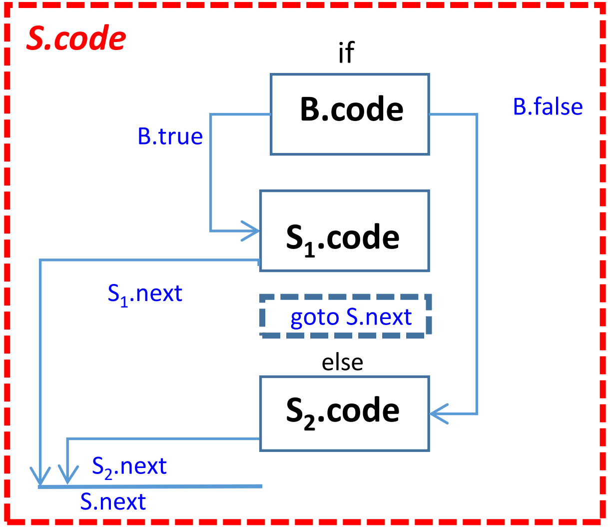
CodeGen: Control Statement[控制语句]

- Inherited attributes[继承属性]
  - ◆ B.true: the label to which control flows if B is true (依赖于S1)
  - ◆ B.false: the label to which control flows if B is false (依赖于S2)
  - ◆ S.next: a label for the instruction immediately after the code of S

① S -> if (B) S_1

② S -> if (B) S_1 else S_2

③ S -> while (B) S_1



Translation of Controls

- Helper functions[辅助函数]
  - newlabel(): creates a new label
  - label(L): attaches label L to the next three address inst to be generated

① S -> if (B) S_1

② S -> if (B) S_1 else S_2

③ S -> while (B) S_1

S -> if { B.true = newlabel();

B.false = newlabel(); }

(B) { label(B.true); S_1.next = S.next; }

S_1 { gen('goto' S.next); }

else { label(B.false); S_2.next = S.next; } S_2

If false B goto B.false

B.true:

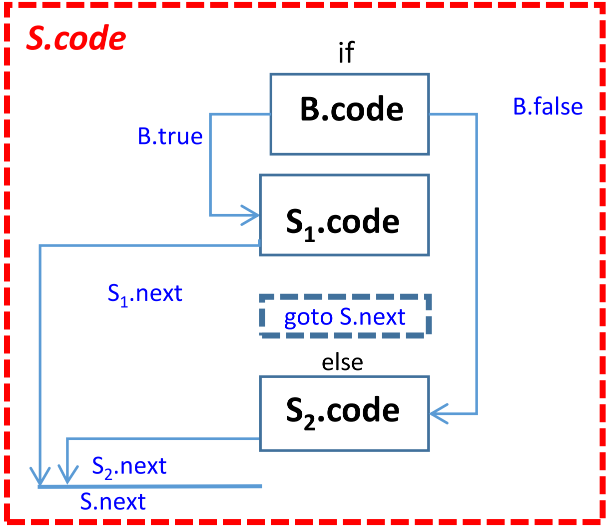
S_1.code

goto S.next

B.false:

S_2.code

S.next:



Translation of Controls (cont.)

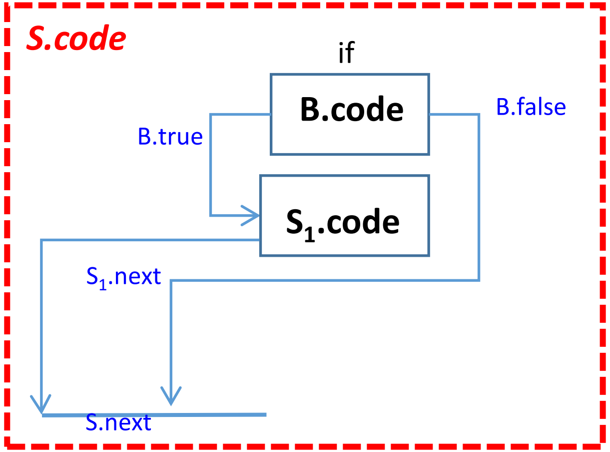
① S -> if (B) S_1

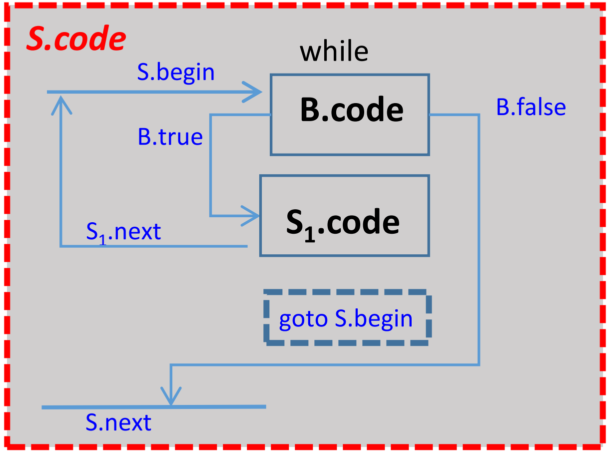
② S -> if (B) S_1 else S_2

③ S -> while (B) S_1

S -> if { B.true = newlabel(); B.false = S.next; }
(B) { label(B.true); S_1.next = S.next; }
S_1

S -> while { S.begin = newlabel();
label(S.begin);
B.true = newlabel();
B.false = S.next; }
(B) { label(B.true); S_1.next = S.begin; }
S_1 { gen('goto' S.begin); }





Jumping Labels[跳转标签]

- Key of generating code for Boolean and flow-control: matching a jump inst with the target of jump[跳转指令匹配到跳转目标]
  - Forward jump: a jump to an instruction in below
  - Label for jump target has not yet been generated

B -> { B_1.true = newlabel(); B_1.false = B.false; } B_1 && { label(B_1.true); B_2.true = B.true; B_2.false = B.false; } B_2

S -> if { B.true = newlabel(); B.false = S.next; } (B) { label(B.true); S_1.next = S.next; } S_1

Handle Jumping Labels

- Idea: generate code using dummy labels first, then patch them with addresses later after labels are generated
- **Two-pass** approach: requires two scans of code
  - Pass 1:
    - Generate code creating dummy labels for forward jumps. (Insert label into a hashtable)
    - When label emitted, record address in hashtable
  - Pass 2:
    - Replace dummy labels with target addresses (Use previously built hashtable for mapping)
- **One-pass** approach
  - Generate holes when forward jumping to an un-generated label
  - Maintain a list of holes for that label
  - Fill in holes with addresses when label generated later on

One-Pass Code Generation[单遍生成]

- One Pass Generation takes less time along with LR parser
- However, given the example below, we need to know the address of E2.label to insert jumps in E1
  - E.g. E1.false = E2.label in E → E1 || E2
- Solution: **Backpatching**[回填]
  - Leave holes in IR in place of forward jump addresses
  - Record indices of jump instructions in a hole list
  - When target address of label for jump is eventually known, backpatch holes using the hole list for that particular label

Backpatching[回填]

- Synthesized attributes[综合属性]. S -> if (B) S1
  - B.truelist: a list of jump or conditional jump insts into which we must insert the label to which control goes if B is true[B为真时控制流应该转向的指令的标号]
  - B.falselist: a list of insts that eventually get the label to which control goes when B is false[B为假时控制流应该转向的指令的标号]
  - S.nextlist: a list of jumps to the inst immediately following the code for S[紧跟在S代码之后的指令的标号]
- Helper functions to implement backpatching
  - makelist(i): creates a new list out of statement index i
  - merge(p1, p2): returns merged list of p1 and p2
  - backpatch(p, i): fill holes in list p with statement index i

Backpatching of Control-Flow

- Slightly modify the grammar

① S -> if (B) M S_1 { backpatch(B.truelist, M.inst)
S.nextlist = merge(B.falselist, S1.nextlist); }

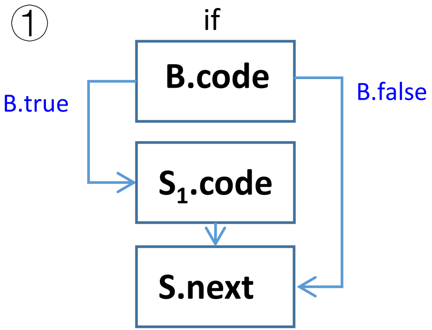
② S -> if (B) M_1 S_1 N else M_2 S_2 { backpatch(B.truelist, M1.inst);
backpatch(B.falselist, M2.inst);
temp = merge(S1.nextlist, N.nextlist);
S.nextlist = merge(temp, S2.nextlist); }

③ S -> while M_1 (B) M_2 S_1 {backpatch(B.truelist, M2.inst);
backpatch(S1.nextlist, M1.inst);
S.nextlist = B.falselist);
gen('goto' M1.inst); }

④ M -> ε { M.inst = nextinst; }
⑤ N -> ε { N.nextlist = makelist(nextinst); gen('goto _'); }

- makelist(i): creates a new list out of statement index i
- merge(p1, p2): returns merged list of p1 and p2
- backpatch(p, i): fill holes in list p with statement index i

①



Backpatching of Control-Flow

- Slightly modify the grammar

① S -> if (B) M S_1 { backpatch(B.truelist, M.inst)
S.nextlist = merge(B.falselist, S1.nextlist); }

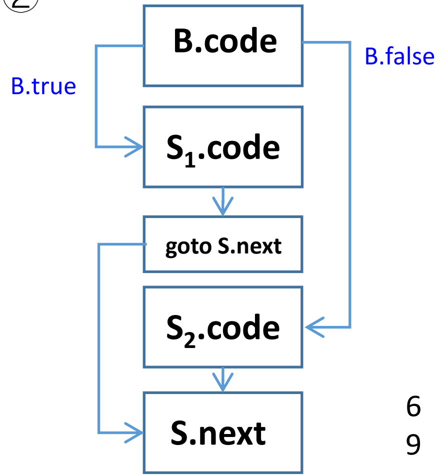
② S -> if (B) M_1 S_1 N else M_2 S_2 { backpatch(B.truelist, M1.inst);
backpatch(B.falselist, M2.inst);
temp = merge(S1.nextlist, N.nextlist);
S.nextlist = merge(temp, S2.nextlist); }

③ S -> while M_1 (B) M_2 S_1 {backpatch(B.truelist, M2.inst);
backpatch(S1.nextlist, M1.inst);
S.nextlist = B.falselist;
gen('goto' M1.inst); }

④ M -> ε { M.inst = nextinst; }
⑤ N -> ε { N.nextlist = makelist(nextinst); gen('goto _'); }

- makelist(i): creates a new list out of statement index i
- merge(p1, p2): returns merged list of p1 and p2
- backpatch(p, i): fill holes in list p with statement index i

② if else



Backpatching of Control-Flow

- Slightly modify the grammar

① S -> if (B) M S_1 { backpatch(B.truelist, M.inst)
S.nextlist = merge(B.falselist, S1.nextlist); }

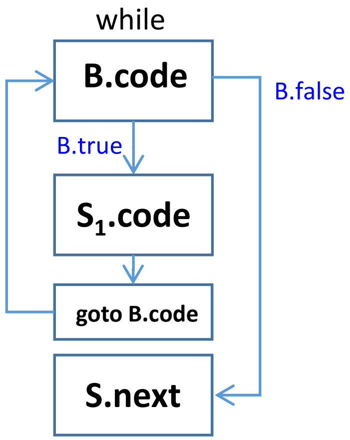
② S -> if (B) M_1 S_1 N else M_2 S_2 { backpatch(B.truelist, M1.inst);
backpatch(B.falselist, M2.inst);
temp = merge(S1.nextlist, N.nextlist);
S.nextlist = merge(temp, S2.nextlist); }

③ S -> while M_1 (B) M_2 S_1 {backpatch(B.truelist, M2.inst);
backpatch(S1.nextlist, M1.inst);
S.nextlist = B.falselist);
gen('goto' M1.inst); }

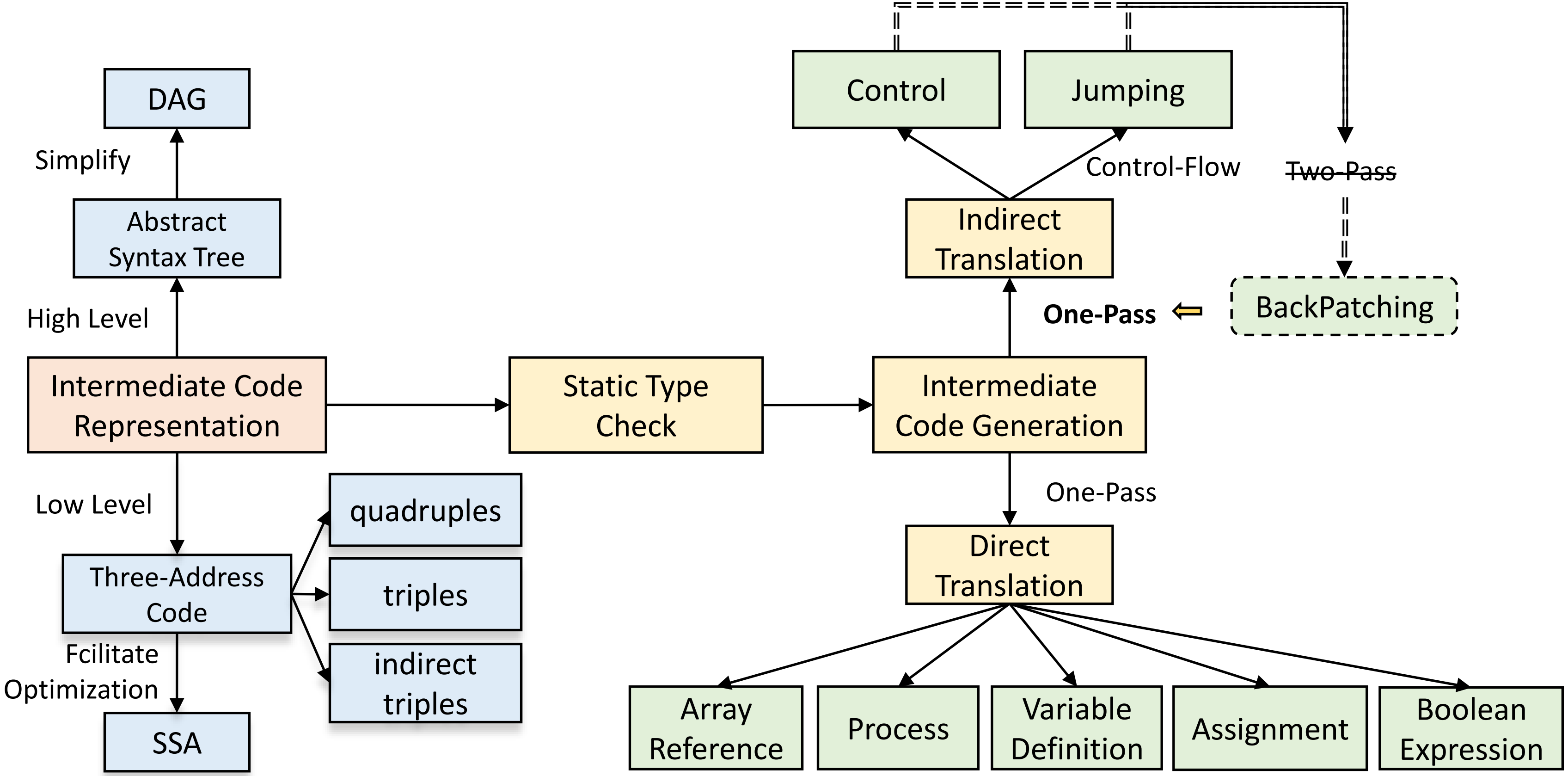
④ M -> ε { M.inst = nextinst; }
⑤ N -> ε { N.nextlist = makelist(nextinst); gen('goto _'); }

- makelist(i): creates a new list out of statement index i
- merge(p1, p2): returns merged list of p1 and p2
- backpatch(p, i): fill holes in list p with statement index i

③



Intermediate Code[中间代码生成]



Summary

- Three-Address Code: X = Y op Z
  - Three representations
    - quadruples [四元式]
    - triples [三元式]
    - indirect triples [间接三元式]
- Single Static Assignment
- Code generation: TAC instructions using syntax directed translation
  - Variable definitions[变量定义]
  - Expressions and statements
    - Assignment[赋值]
    - Array references[数组引用]
    - Boolean expressions[布尔表达式]
    - Control-flow[控制流]

Further Reading

- Dragon Book, 2nd Edition
  - Comprehensive Reading:
    - Section 6.2 on introduction to intermediate representations.
    - Section 6.5 on type checking.
    - Section 6.3, 6.4, 6.6 and 6.7 on translations of various program constructs.
  - Skip Reading:
    - Section 6.1 on AST and DAG.
    - Section 6.8 and 6.9 on translations of switches and procedures.