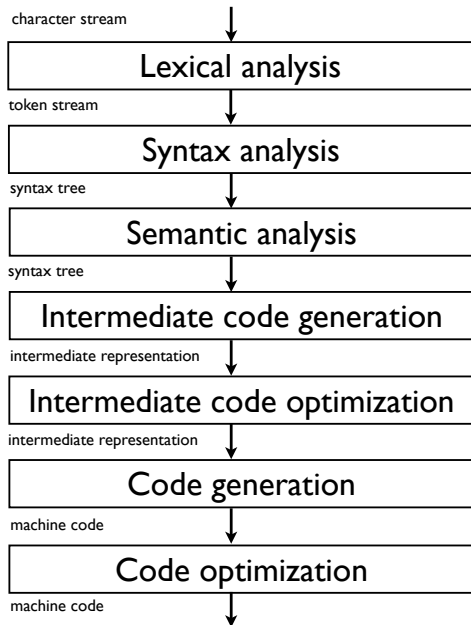


Part 5

Intermediate code generation

Structure of a compiler



Outline

1. Intermediate representations
2. Illustration
3. Optimization

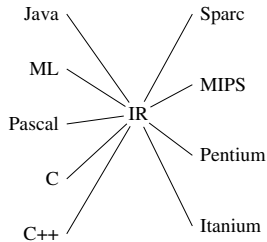
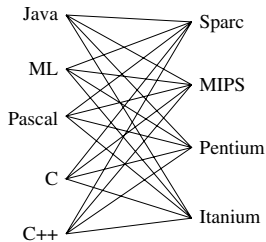
Intermediate code generation

- The final phase of the compiler front-end
- Goal: translate the program into a format expected by the compiler back-end
- In typical compilers: followed by intermediate code optimization and machine code generation
- Techniques for intermediate code generation can be used for final code generation

Intermediate representations

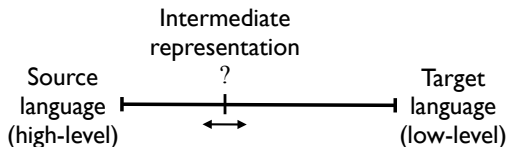
Why use an intermediate representation?

- It's easy to change the source or the target language by adapting only the front-end or back-end (portability)
- It makes optimization easier: one needs to write optimization methods only for the intermediate representation
- The intermediate representation can be directly interpreted



(Appel)

Intermediate representations



- How to choose the intermediate representation?
 - ▶ It should be easy to translate the source language to the intermediate representation
 - ▶ It should be easy to translate the intermediate representation to the machine code
 - ▶ The intermediate representation should be suitable for optimization
- It should be neither too high level nor too low level
- One can have more than one intermediate representation in a single compiler

Some common intermediate representations

General forms of intermediate representations (IR):

- Graphical IR (parse tree, abstract syntax trees, DAG. . .)
- Linear IR (ie., non graphical)
- Three Address Code (TAC): instructions of the form “result=op1 operator op2”
- Static single assignment (SSA) form: each variable is assigned once
- Continuation-passing style (CPS): general form of IR for functional languages

Some common intermediate representations

Examples:

- Java bytecode (executed on the Java Virtual Machine)
- LLVM (Low Level Virtual Machine): SSA and TAC based
- C is used in several compilers as an intermediate representation (Lisp, Haskell, Cython. . .)
- Microsoft's Common Intermediate Language (CIL)
- GNU Compiler Collection (GCC) uses several intermediate representations:
 - ▶ Abstract syntax trees
 - ▶ GENERIC (tree-based)
 - ▶ GIMPLE (SSA form)
 - ▶ Register Transfer Language (RTL, inspired by lisp lists)

(Google them)

Static Single-Assignment Form (SSA)

- A naming discipline used to explicitly encode information about both the flow of control and the flow of data values
- A program is in SSA form if:
 1. each definition has a distinct name
 2. each use refers to a single definition
- Example:

Original code

$y = 1$

$y = 2$

$x = y$

SSA form

$y_1 = 1$

$y_2 = 2$

$x_1 = y_2$

- Main interest: allows to implement several code optimizations.
 - ▶ In the example above, it is clear from the SSA form that the first assignment is not necessary.

Converting to SSA

- Converting a program into a SSA form is not a trivial task

Original code

```
x = 5
x = x - 3
if x < 3
    y = x * 2
    w = y
else
    y = x - 3
w = x - y
z = x + y
```

SSA form

```
x1 = 5
x2 = x1 - 3
if x2 < 3
    y1 = x2 * 2
    w1 = y1
else
    y2 = x2 - 3
w2 = x2 - y?
z1 = x2 + y?
```

- Need to introduce a special statement: Φ -functions

Converting to SSA

Original code

```
x = 5
x = x - 3
if x < 3
    y = x * 2
    w = y
else
    y = x - 3
w = x - y
z = x + y
```

SSA form

```
x1 = 5
x2 = x1 - 3
if x2 < 3
    y1 = x2 * 2
    w1 = y1
else
    y2 = x2 - 3
    y3 =  $\Phi(y_1, y_2)$ 
    w2 = x2 - y3
    z1 = x2 + y3
```

- $\Phi(y_1, y_2)$ is defined as y_1 if we arrive at this instruction through the THEN branch, y_2 if through the ELSE branch.
- One needs to introduce Φ functions at every point of the program where several “paths” merge.

SSA form

- Given an arbitrary program, finding where to place the Φ functions is a difficult task.
- However, an efficient solution is available, based on the control flow graph of the program (see later).
- In practice, the Φ functions are not implemented. They indicate to the compiler that the variables given as arguments need to be stored in the same place.
- In the previous example, we can infer that y_1 and y_2 should be stored in the same place

Continuation-passing style (CPS)

- A programming style in functional languages where control is passed explicitly as argument to the functions, in the form of a *continuation*.
- A continuation is an abstract representation of the control state of a program, most of the time in the form of a first-class function.
- Like SSA, CPS is often used in intermediate representation in compilers of functional languages.

CPS: examples

Direct style

```
(define (pyth x y)
  (sqrt (+ (* x x)(* y y))))
```

CPS style (k is the continuation)

```
(define (pyth& x y k)
  (*& x x (lambda (x2)
            (*& y y (lambda (y2)
                      (+& x2 y2 (lambda (x2py2)
                                   (sqrt& x2py2 k))))))))))
```

```
(define (*& x y k)
  (k (* x y)))
(define (+& x y k)
  (k (+ x y)))
(define (sqrt& x k)
  (k (sqrt x)))
```

- The main interest of CPS is to make explicit several things that are typically implicit in functional languages: returns, intermediate values (= continuation arguments), order of argument evaluation...
- Like for SSA, the main interest is to ease optimizations.
- Theoretically, SSA and CPS are equivalent: a program in SSA form can be transformed into a CPS program and vice versa.
- Previous program can be rewritten as:

$$x2 = x * x$$
$$y2 = y * y$$
$$x2py2 = x2 + y2$$
$$res = sqrt(x2py2)$$

Outline

1. Intermediate representations

2. Illustration

3. Optimization

The intermediate language

We will illustrate the translation of typical high-level language constructions using the following low-level intermediate language:

<i>Program</i>	→	[<i>Instructions</i>]	<i>Instruction</i>	→	LABEL labelid
			<i>Instruction</i>	→	GOTO labelid
<i>Instructions</i>	→	<i>Instruction</i>	<i>Instruction</i>	→	IF id relop Atom THEN labelid ELSE labelid
<i>Instructions</i>	→	<i>Instruction</i> , <i>Instructions</i>	<i>Instruction</i>	→	id := CALL functionid(Args)
<i>Instruction</i>	→	id := Atom	<i>Atom</i>	→	id
<i>Instruction</i>	→	id := unop Atom	<i>Atom</i>	→	num
<i>Instruction</i>	→	id := id binop Atom	<i>Args</i>	→	id
<i>Instruction</i>	→	id := M[Atom]	<i>Args</i>	→	id , Args
<i>Instruction</i>	→	M[Atom] := id			

Simplified three-address code, very close to machine code

See chapter 5 and 7 of (Mogensen, 2010) for full details

The intermediate language

Program → [*Instructions*]

Instructions → *Instruction*

Instructions → *Instruction* , *Instructions*

Instruction → **id** := *Atom*

Instruction → **id** := **unop** *Atom*

Instruction → **id** := **id binop** *Atom*

Instruction → **id** := *M*[*Atom*]

Instruction → *M*[*Atom*] := **id**

Atom → **id**

Atom → **num**

- All values are assumed to be integer
- Unary and binary operators include normal arithmetic and logical operations
- An atomic expression is either a variable or a constant
- $M[Atom] := \mathbf{id}$ is a transfer from a variable to memory
- $\mathbf{id} := M[Atom]$ is a transfer from memory to a variable

The intermediate language

<i>Instruction</i>	→	LABEL labelid
<i>Instruction</i>	→	GOTO labelid
<i>Instruction</i>	→	IF id relop Atom THEN labelid ELSE labelid
<i>Instruction</i>	→	id := CALL functionid(Args)
<i>Atom</i>	→	id
<i>Atom</i>	→	num
<i>Args</i>	→	id
<i>Args</i>	→	id , Args

- LABEL only marks a position in the program
- **relop** includes relational operators $\{=, \neq, <, >, \leq \text{ or } \geq\}$
- Arguments of a function call are variables and the result is assigned to a variable

Principle of translation

- Syntax-directed translation using several attributes:
 - ▶ Code returned as a synthesized attribute
 - ▶ Symbol tables passed as inherited attributes
 - ▶ Places to store intermediate values as synthesized or inherited attributes
- Implemented as recursive functions defined on syntax tree nodes (as for type checking)
- Since translation follows the syntax, it is done mostly independently of the context, which leads to suboptimal code
- Code is supposed to be optimized globally afterwards

Expressions

$Exp \rightarrow \mathbf{num}$

$Exp \rightarrow \mathbf{id}$

$Exp \rightarrow \mathbf{unop} \ Exp$

$Exp \rightarrow \ Exp \ \mathbf{binop} \ Exp$

$Exp \rightarrow \mathbf{id}(Exps)$

$Exps \rightarrow \ Exp$

$Exps \rightarrow \ Exp \ , \ Exps$

(source language grammar !)

Principle of translation:

- Every operation is stored in a new variable in the intermediate language, generated by a function *newvar*
- The new variables for sub-expressions are created by parent expression and passed to sub-expression as **inherited** attributes (synthesized attributes are also possible)

Expressions

$Trans_{Exp}(Exp, vtable, ftable, place) = \text{case } Exp \text{ of}$	
num	$v = \text{getvalue}(\mathbf{num})$ $[place := v]$
id	$x = \text{lookup}(vtable, \text{getname}(\mathbf{id}))$ $[place := x]$
unop Exp_1	$place_1 = \text{newvar}()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, place_1)$ $op = \text{transop}(\text{getopname}(\mathbf{unop}))$ $code_1 ++ [place := op\ place_1]$

where to place the translation of Exp_1 (inherited attribute)

String concatenation

- *getopname* retrieves the operator associated to the token **unop**. *transop* translates this operator into the equivalent operator in the intermediate language
- $[place := v]$ is a string where *place* and *v* have been replaced by their values (in the compiler)
 - ▶ Example: if $place = t14$ and $v = 42$, $[place := v]$ is the instruction $[t14:=42]$.

Expressions: binary operators and function call

$Trans_{Exp}(Exp, vtable, ftable, place) = \text{case } Exp \text{ of}$	
$Exp_1 \text{ binop } Exp_2$	$place_1 = \text{newvar}()$ $place_2 = \text{newvar}()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, place_1)$ $code_2 = Trans_{Exp}(Exp_2, vtable, ftable, place_2)$ $op = \text{transop}(\text{getopname}(\mathbf{binop}))$ $code_1 ++ code_2 ++ [place := place_1 \text{ op } place_2]$
$\mathbf{id}(Exps)$	$(code_1, [a_1, \dots, a_n])$ $\quad = Trans_{Exps}(Exps, vtable, ftable)$ $fname = \text{lookup}(ftable, \text{getname}(\mathbf{id}))$ $code_1 ++ [place := \text{CALL } fname(a_1, \dots, a_n)]$

Expressions: function arguments

$Trans_{Exps}(Exps, vtable, ftable) = \text{case } Exps \text{ of}$	
Exp	$place = newvar()$ $code_1 = Trans_{Exp}(Exp, vtable, ftable, place)$ $(code_1, [place])$
$Exp , Exps$	$place = newvar()$ $code_1 = Trans_{Exp}(Exp, vtable, ftable, place)$ $(code_2, args) = Trans_{Exps}(Exps, vtable, ftable)$ $code_3 = code_1 ++ code_2$ $args_1 = place :: args$ $(code_3, args_1)$

Expressions: example of translation

Translation of $3+f(x-y,z)$:

```
t1 := 3
    t4 := v0
    t5 := v1
    t3 := t4 - t5
    t6 := v2
    t2 := CALL _f(t3,t6)
t0 := t1+t2
```

Assuming that:

- x , y , and z are bound to variables $v0$, $v1$, and $v2$
- Expression is stored in $t0$
- New variables are generated as $t1$, $t2$, $t3\dots$
- Indentation indicates depth of call to $Trans_{Exp}$

Statements

$Stat \rightarrow Stat ; Stat$

$Stat \rightarrow \mathbf{id} := Exp$

$Stat \rightarrow \mathbf{if} Cond \mathbf{then} Stat$

$Stat \rightarrow \mathbf{if} Cond \mathbf{then} Stat \mathbf{else} Stat$

$Stat \rightarrow \mathbf{while} Cond \mathbf{do} Stat$

$Stat \rightarrow \mathbf{repeat} Stat \mathbf{until} Cond$

$Cond \rightarrow Exp \mathbf{relop} Exp$

Principle of translation:

- New unused labels are generated by the function *newlabel* (similar to *newvar*)
- These labels are created by parents and passed as inherited attributes

Statements: sequence of statements and assignment

$Trans_{Stat}(Stat, vtable, ftable) = \text{case } Stat \text{ of}$	
$Stat_1 ; Stat_2$	$code_1 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_2, vtable, ftable)$ $code_1 ++ code_2$
$\mathbf{id} := Exp$	$place = lookup(vtable, getname(\mathbf{id}))$ $Trans_{Exp}(Exp, vtable, ftable, place)$

Statements: conditions

$Trans_{Stat}(Stat, vtable, ftable) = \text{case } Stat \text{ of}$	
<i>if</i> <i>Cond</i>	$label_1 = \text{newlabel}()$
<i>then</i> <i>Stat</i> ₁	$label_2 = \text{newlabel}()$
<i>else</i> <i>Stat</i> ₂	$label_3 = \text{newlabel}()$
	$code_1 = Trans_{Cond}(Cond, label_1, label_2, vtable, ftable)$
	$code_2 = Trans_{Stat}(Stat_1, vtable, ftable)$
	$code_3 = Trans_{Stat}(Stat_2, vtable, ftable)$
	$code_1 ++ [LABEL label_1] ++ code_2$
	$++ [GOTO label_3, LABEL label_2]$
	$++ code_3 ++ [LABEL label_3]$

$Trans_{Cond}(Cond, label_t, label_f, vtable, ftable) = \text{case } Cond \text{ of}$	
<i>Exp</i> ₁ relop <i>Exp</i> ₂	$t_1 = \text{newvar}()$
	$t_2 = \text{newvar}()$
	$code_1 = Trans_{Exp}(Exp_1, vtable, ftable, t_1)$
	$code_2 = Trans_{Exp}(Exp_2, vtable, ftable, t_2)$
	$op = \text{transop}(\text{getopname}(\mathbf{relop}))$
	$code_1 ++ code_2 ++ [IF t_1 op t_2 THEN label_t ELSE label_f]$

Statements: while loop

$Trans_{Stat}(Stat, vtable, ftable) = \text{case } Stat \text{ of}$	
<code>while Cond</code> <code>do Stat₁</code>	<code>label₁ = newlabel()</code> <code>label₂ = newlabel()</code> <code>label₃ = newlabel()</code> <code>code₁ = Trans_{Cond}(Cond, label₂, label₃, vtable, ftable)</code> <code>code₂ = Trans_{Stat}(Stat₁, vtable, ftable)</code> <code>[LABEL label₁]<code>++code₁</code></code> <code> <code>++[LABEL label₂]<code>++code₂</code></code> <code> <code>++[GOTO label₁, LABEL label₃]</code></code></code>

Logical operators

- Logical conjunction, disjunction, and negation are often available to define conditions
- Two ways to implement them:
 - ▶ Usual arithmetic operators: arguments are evaluated and then the operators is applied. Example in C: bitwise operators: '&' and '|'.
 - ▶ **Sequential logical operators**: the second operand is not evaluated if the first determines the result (**lazy** or **short-circuit** evaluation). Example in C: logical operators '&&' and '||'.
- First type is simple to implement:
 - ▶ by allowing any expression as condition

$$Cond \rightarrow Exp$$

- ▶ by including '&', '|', and '!' among binary and unary operators
- Second one requires more modifications

Sequential logical operators

$Cond \rightarrow Exp \mathbf{relop} Exp$

$Cond \rightarrow \mathbf{true}$

$Cond \rightarrow \mathbf{false}$

$Cond \rightarrow \mathbf{!} Cond$

$Cond \rightarrow Cond \mathbf{\&\&} Cond$

$Cond \rightarrow Cond \mathbf{||} Cond$

$Trans_{Cond}(Cond, label_t, label_f, vtable, ftable) = \text{case } Cond \text{ of}$	
\mathbf{true}	$[\mathbf{GOTO } label_t]$
\mathbf{false}	$[\mathbf{GOTO } label_f]$
$\mathbf{!} Cond_1$	$Trans_{Cond}(Cond_1, label_f, label_t, vtable, ftable)$
$Cond_1 \mathbf{\&\&} Cond_2$	$arg_2 = \text{newlabel}()$ $code_1 = Trans_{Cond}(Cond_1, arg_2, label_f, vtable, ftable)$ $code_2 = Trans_{Cond}(Cond_2, label_t, label_f, vtable, ftable)$ $code_1 ++ [\mathbf{LABEL } arg_2] ++ code_2$
$Cond_1 \mathbf{ } Cond_2$	$arg_2 = \text{newlabel}()$ $code_1 = Trans_{Cond}(Cond_1, label_t, arg_2, vtable, ftable)$ $code_2 = Trans_{Cond}(Cond_2, label_t, label_f, vtable, ftable)$ $code_1 ++ [\mathbf{LABEL } arg_2] ++ code_2$

Other statements

More advanced control statements:

- **Goto and labels:** labels are stored in the symbol table (and associated with intermediate language labels). Generated as soon as a jump or a declaration is met (to avoid one additional pass)
- **Break/exit:** pass an additional (inherited) attribute to the translation function of loops with the label a break/exit should jump to. A new label is passed when entering a new loop.
- **Case/switch-statements:** translated with nested if-then-else statements.
- ...

Arrays

Language can be extended with one-dimensional arrays:

$$\begin{array}{ll} \textit{Exp} & \rightarrow \textit{Index} \\ \textit{Stat} & \rightarrow \textit{Index} := \textit{Exp} \\ \textit{Index} & \rightarrow \mathbf{id}[\textit{Exp}] \end{array}$$

Principle of translation:

- Arrays can be allocated **statically** (at compile-time) or **dynamically** (at run-time)
- Base address of the array is stored as a constant in the case of static allocation, or in a variable in the case of dynamic allocation
- The symbol table binds the array name to the constant or variable containing its address

Arrays: translation

$Trans_{Exp}(Exp, vtable, ftable, place) = \text{case } Exp \text{ of}$	
$Index$	$(code_1, address) = Trans_{Index}(Index, vtable, ftable)$ $code_1 ++ [place := M[address]]$

$Trans_{Stat}(Stat, vtable, ftable) = \text{case } Stat \text{ of}$	
$Index := Exp$	$(code_1, address) = Trans_{Index}(Index, vtable, ftable)$ $t = newvar()$ $code_2 = Trans_{Exp}(Exp, vtable, ftable, t)$ $code_1 ++ code_2 ++ [M[address] := t]$

$Trans_{Index}(Index, vtable, ftable) = \text{case } Index \text{ of}$	
$id[Exp]$	$base = lookup(vtable, getname(id))$ $t = newvar()$ $code_1 = Trans_{Exp}(Exp, vtable, ftable, t)$ $code_2 = code_1 ++ [t := t * 4, t := t + base]$ $(code_2, t)$

(Assuming arrays are indexed starting at 0 and integers are 32 bits long)

Multi-dimensional arrays

Index \rightarrow **id**[*Exp*]

Index \rightarrow *Index*[*Exp*]

Principle of translation:

- Two ways to represent a 2-dimensional array in linear memory:
 - ▶ **Row-major** order: one row at a time. For a 3×2 array: $a[0][0]$, $a[0][1]$, $a[1][0]$, $a[1][1]$, $a[2][0]$, $a[2][1]$
 - ▶ **Column-major** order: one column at a time. For a 3×2 array: $a[0][0]$, $a[1][0]$, $a[2][0]$, $a[0][1]$, $a[1][1]$, $a[2][1]$
- Generalization: if $dim_0, dim_1, \dots, dim_{n-1}$ are the sizes of the dimensions in a n -dimensional array, the element $[i_0][i_1] \dots [i_{n-1}]$ has the address:
 - ▶ Row-major:
 $base + ((\dots (i_0 \cdot dim_1 + i_1) \cdot dim_2 \dots + i_{n-2}) \cdot dim_{n-1} + i_{n-1}) \cdot size$
 - ▶ Column-major:
 $base + ((\dots (i_{n-1} \cdot dim_0 + i_{n-2}) \cdot dim_1 \dots + i_1) \cdot dim_{n-2} + i_0) \cdot size$
- Dimension sizes are stored as constant (static), in variables or in memory next to the array data (dynamic)

Multi-dimensional arrays: translation

$Trans_{Index}(Index, vtable, ftable) =$
$(code_1, t, base, \square) = Calc_{Index}(Index, vtable, ftable)$
$code_2 = code_1 ++ [t := t * 4, t := t + base]$
$(code_2, t)$

$Calc_{Index}(Index, vtable, ftable) = \text{case } Index \text{ of}$	
$id[Exp]$	$(base, dims) = lookup(vtable, getname(id))$ $t = newvar()$ $code = Trans_{Exp}(Exp, vtable, ftable, t)$ $(code, t, base, tail(dims))$
$Index[Exp]$	$(code_1, t_1, base, dims) = Calc_{Index}(Index, vtable, ftable)$ $dim_1 = head(dims)$ $t_2 = newvar()$ $code_2 = Trans_{Exp}(Exp, vtable, ftable, t_2)$ $code_3 = code_1 ++ code_2 ++ [t_1 := t_1 * dim_1, t_1 := t_1 + t_2]$ $(code_3, t_1, base, tail(dims))$

(Assume dimension sizes are stored in the symbol table, as constant or variable)

Other structures

- **Floating point values:** can be treated the same way as integers (assuming the intermediate language has specific variables and operators for floating point numbers)
- **Records/structures:** allocated in a similar way as arrays
 - ▶ Each field is accessed by adding an offset to the base-address of the record
 - ▶ Base-addresses and offsets for each field are stored in the symbol table for all record-variables
- **Strings:** similar to arrays of bytes but with a length that can vary at run-time
- ...

Variable declaration

Stat → *Decl ; Stat*

Decl → int **id**

Decl → int **id**[**num**]

Principle of translation:

- Information about where to find scalar variables (e.g. integer) and arrays after declaration is stored in the symbol table
- Allocations can be done in many ways and places (static, dynamic, local, global. . .)

Variable declaration

$Trans_{Stat}(Stat, vtable, ftable) = \text{case } Stat \text{ of}$	
$Decl ; Stat_1$	$(code_1, vtable_1) = Trans_{Decl}(Decl, vtable)$ $code_2 = Trans_{Stat}(Stat_1, vtable_1, ftable)$ $code_1 ++ code_2$

$Trans_{Decl}(Decl, vtable) = \text{case } Decl \text{ of}$	
int id	$t_1 = newvar()$ $vtable_1 = bind(vtable, getname(\mathbf{id}), t_1)$ $([], vtable_1)$
int id[num]	$t_1 = newvar()$ $vtable_1 = bind(vtable, getname(\mathbf{id}), t_1)$ $([t_1 := HP, HP := HP + (4 * getvalue(\mathbf{num}))], vtable_1)$

(Assumes scalar variables are stored in intermediate language variables and arrays are dynamically allocated on the **heap**, with their base-addresses stored in a variable. *HP* points to the first free position of the heap.)

Comments

- Needs to add error checking in previous illustration (array index out of bounds in arrays, wrong number of dimensions, memory/heap overflow, etc.)
- In practice, results of translation are not returned as strings but either:
 - ▶ output directly into an array or a file
 - ▶ or stored into a structure (translation tree or linked list)

The latter allows subsequent code restructuring during optimization

- We have not talked about:
 - ▶ memory organization: typically subdivided into static data (for static allocation), heap (for dynamic allocation) and stack (for function calls)
 - ▶ translation of function calls: function arguments, local variables, and return address are stored on the stack (similar to what you have seen in INFO-0012, computation structures)

Outline

1. Intermediate representations

2. Illustration

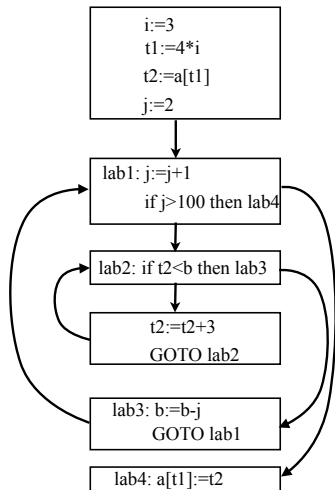
3. Optimization

IR code optimization

- IR code generation is usually followed by code optimization
- Why?
 - ▶ IR generation introduces redundancy
 - ▶ To compensate for laziness of programmers
- **Improvement** rather than optimization since optimization is undecidable
- Challenges in optimization:
 - ▶ Correctness: should not change the semantic of the program
 - ▶ Efficiency: should produce IR code as efficient as possible
 - ▶ Computing times: should not take too much time to optimize
- What to optimize?
 - ▶ Computing times
 - ▶ Memory usage
 - ▶ Power consumption
 - ▶ ...

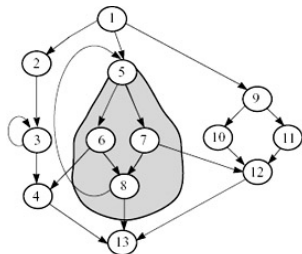
Control-flow graph

- A **basic block** is a series of IR instructions where:
 - ▶ there is one entry point into the basic block, and
 - ▶ there is one exit point out of the basic block.
- **Control-flow graph**: nodes are basic blocks and edges are jumps between blocks



Control-flow graph and SSA

- The control-flow graph (CFG) can be used to determine where to introduce Φ functions when deriving a SSA form:
 - ▶ A node A (basic block) of the CFG *strictly dominates* a node B if it is impossible to reach B without going through A . A *dominates* B if A strictly dominates B or $A = B$.
 - ▶ B is in the *dominance frontier* of A if A does not strictly dominate B , but dominates some immediate predecessor of B .
 - ▶ Whenever node A contains a definition of a variable x , any node B in the dominance frontier of A needs a Φ function for x .
- There exist an efficient algorithm to find the dominance frontier of a node



4,5,12,13 are in the
dominance frontier of 5
(Appel)

Local optimizations

Local optimization: optimization within a single basic block

Examples:

- **Constant folding:** evaluation at compile-time of expressions whose operands are constant
 - ▶ $10+2*3 \rightarrow 16$
 - ▶ `[If 1 then Lab1 Else Lab2] → [GOTO Lab1]`
- **Constant propagation:** if a variable is assigned a constant, then propagate the constant into each use of the variable
 - ▶ `[x:=4;t:=y*x;]` can be transformed into `[t:=y*4;]` if x is not used later

Local optimizations

Examples:

- **Copy propagation:** similar to constant propagation but generalized to non constant values

```
tmp2 = tmp1;
```

```
tmp3 = tmp2 * tmp1;
```

```
tmp4 = tmp3;
```

```
tmp5 = tmp3 * tmp2;
```

```
c = tmp5 + tmp4;
```

```
tmp3 = tmp1 * tmp1;
```

```
tmp5 = tmp3 * tmp1;
```

```
c = tmp5 + tmp3;
```

- **Dead code elimination:** remove instructions whose result is never used
 - ▶ Example: Remove [tmp1=tmp2+tmp3;] if tmp1 is never used

Local optimizations

Examples:

- **Common subexpression elimination:** if two operations produce the same results, compute the result once and reference it the second time
 - ▶ Example: in `a[i]=a[i]+2`, the address of `a[i]` is computed twice. When translating, do it once and store the result in a temporary variable
- **Code moving/hoisting:** move outside of a loop all computations independent of the variables that are changing inside the loop
 - ▶ Example: part of the computation of the address for `a[i][j]` can be removed from this loop

```
while (j<k) {  
    sum = sum + a[i][j];  
    j++;  
}
```

IR code optimization

- Local optimizations can be interleaved in different ways and applied several times each
- Optimal optimization order is very difficult to determine
- Global optimization: optimization across basic blocks
 - ▶ Implies performing data-flow analysis, i.e., determine how values propagate through the control-flow graph
 - ▶ More complicated than local optimization