Compilation

0368-3133 2014/15a

Lecture 6

Getting into the back-end

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But first, a short reminder

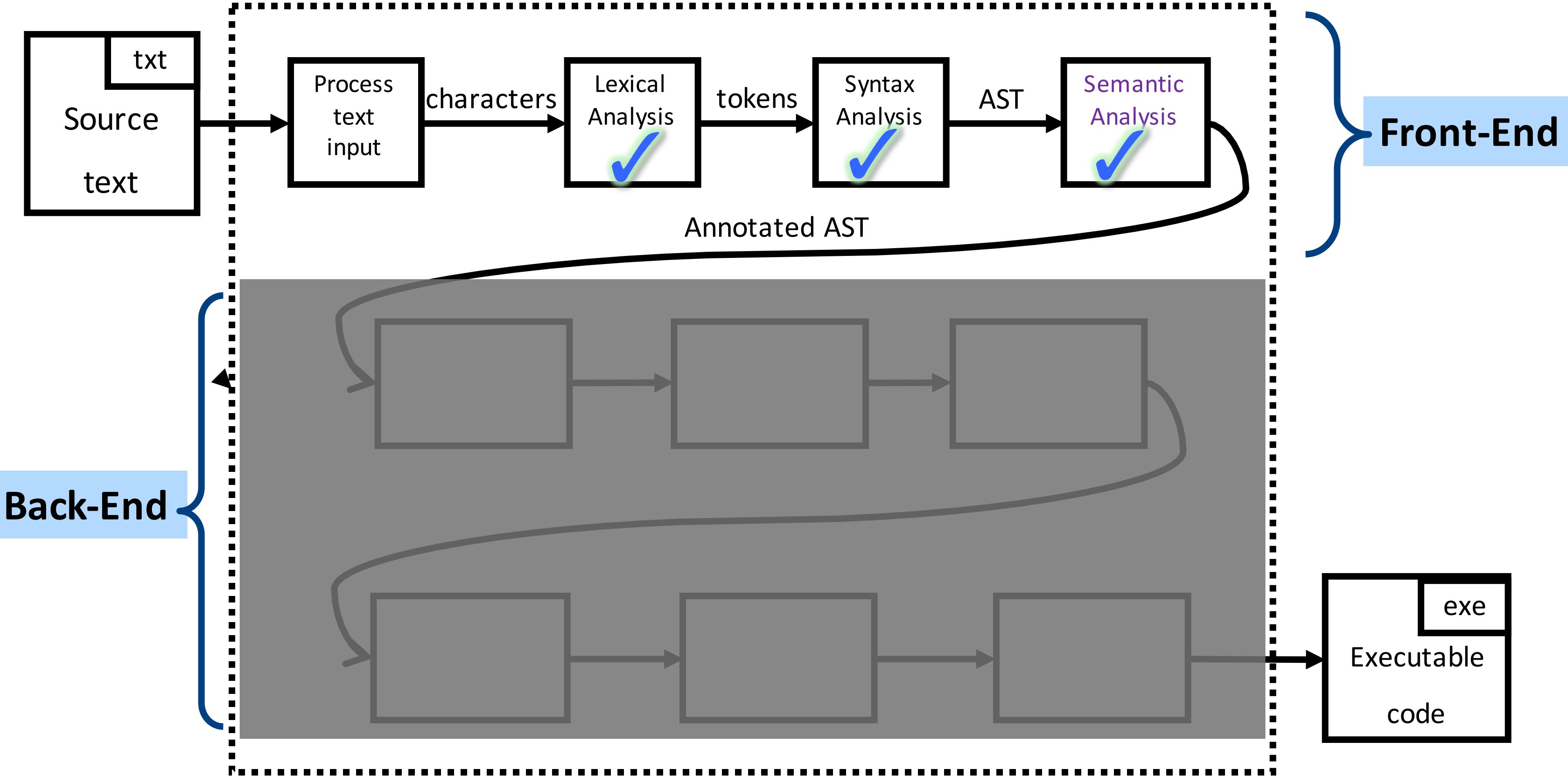
What is a compiler?

“A compiler is a computer program that transforms source code written in a programming language (source language) into another language (target language).

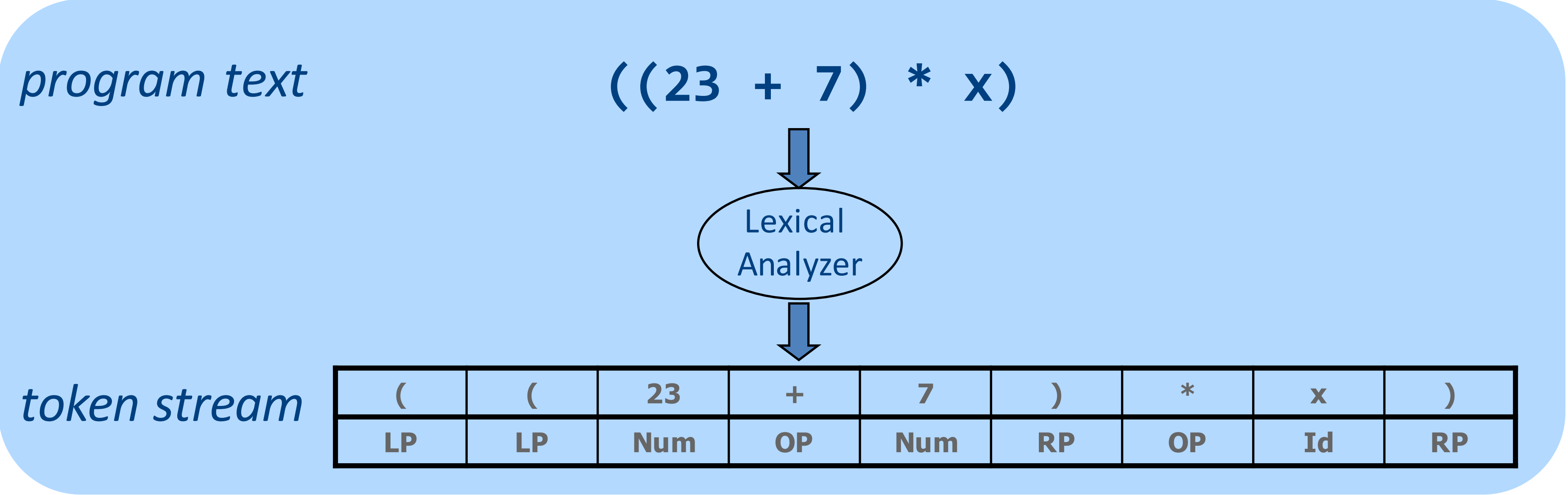
The most common reason for wanting to transform source code is to create an executable program.”

--Wikipedia

Where we were



Lexical Analysis



program text

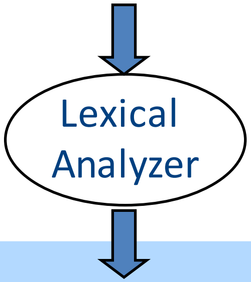
`((23 + 7) * x)`

token stream

(	(	23	+	7	)	*	x	)
LP	LP	Num	OP	Num	RP	OP	Id	RP

From scanning to parsing

program text **((23 + 7) * x)**



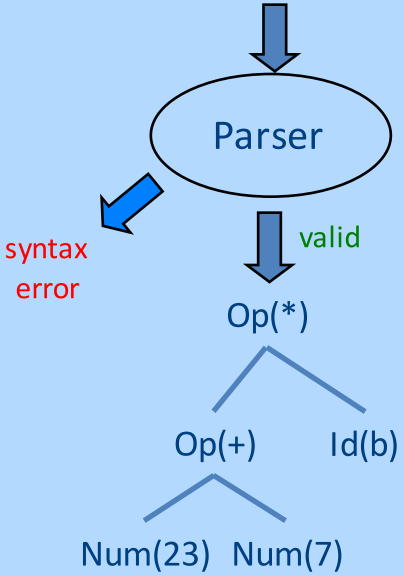
token stream

(	(	23	+	7	)	*	x	)
LP	LP	Num	OP	Num	RP	OP	Id	RP

Grammar:

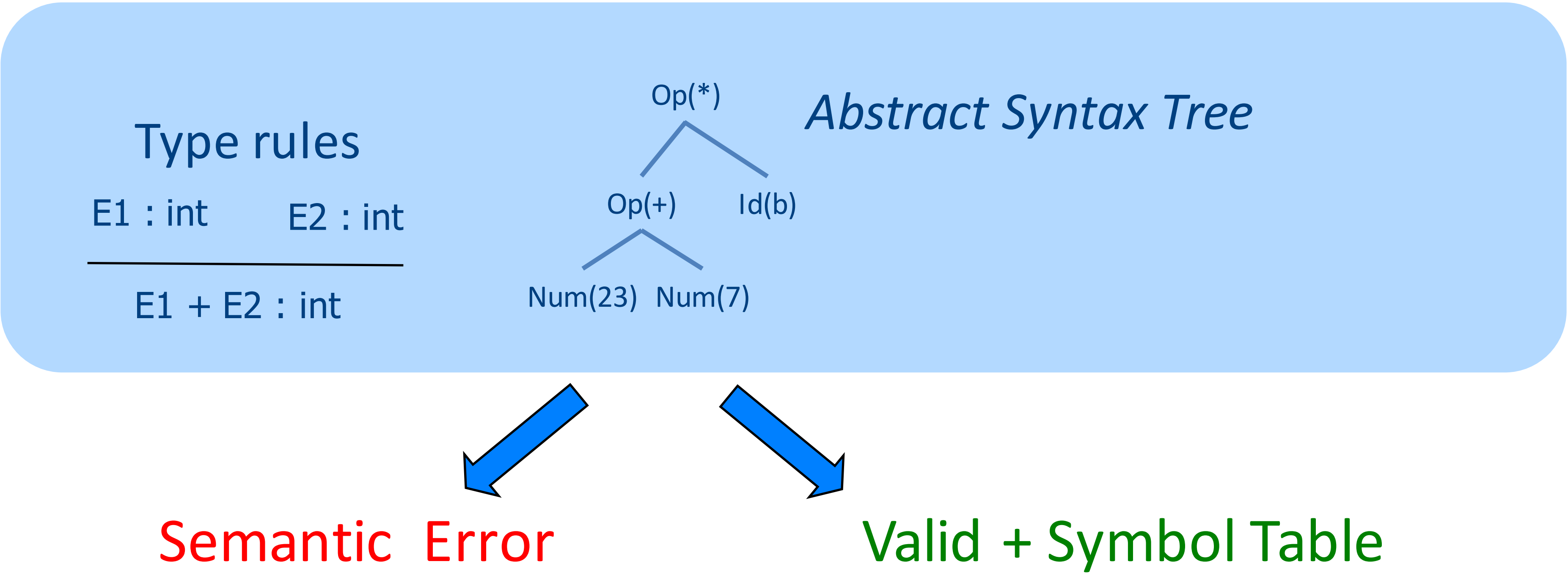
E → … | Id

Id → ‘a’ | … | ‘z’



Abstract Syntax Tree

Context Analysis



Type rules

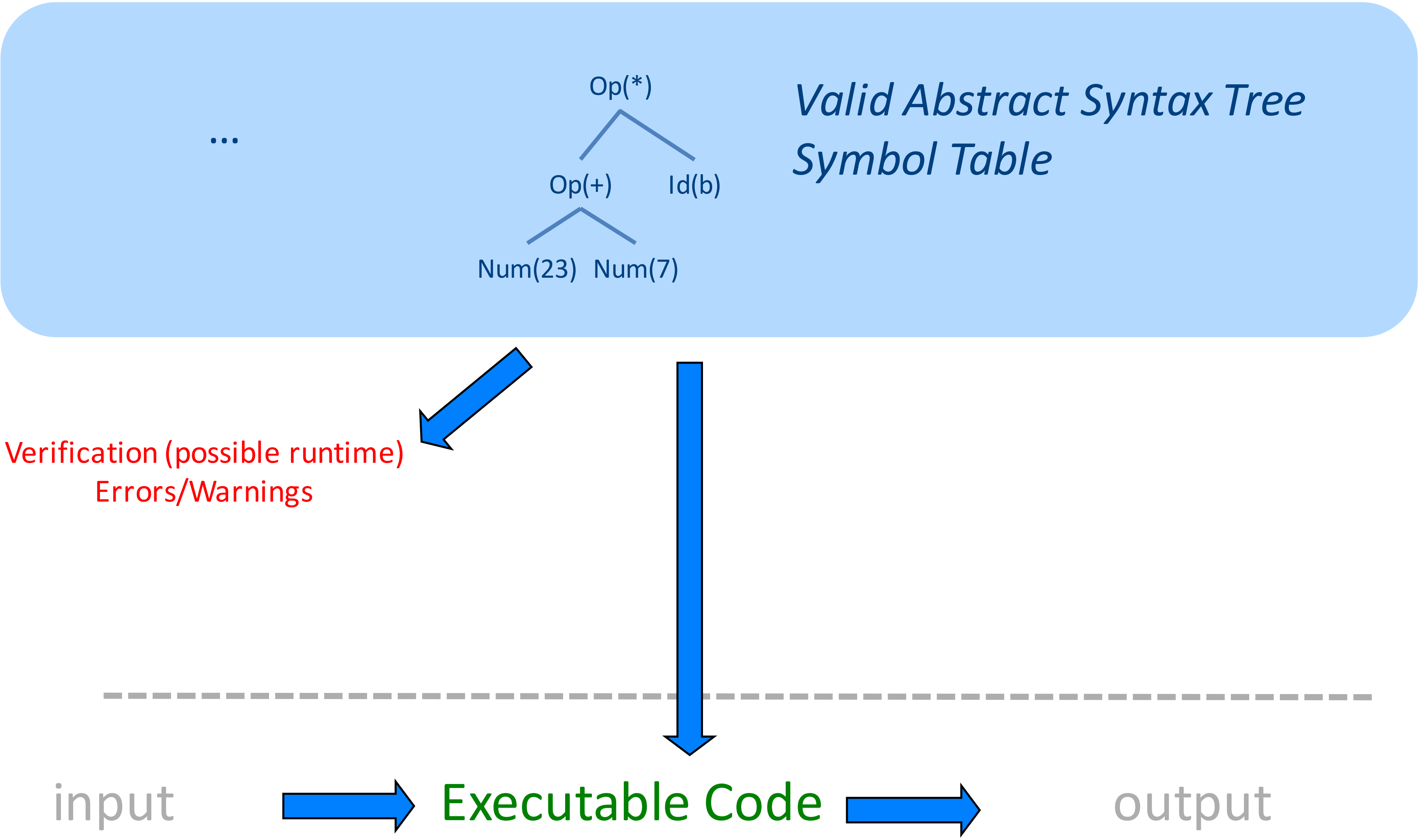
$$\frac{E1 : \text{int} \qquad E2 : \text{int}}{E1 + E2 : \text{int}}$$

Abstract Syntax Tree

Semantic Error

Valid + Symbol Table

Code Generation



Valid Abstract Syntax Tree

Symbol Table

Verification (possible runtime)
Errors/Warnings

input

Executable Code

output

What is a compiler?

“A **compiler** is a computer program that **transforms** source **code** written in a programming language (source language) into another language (target language).

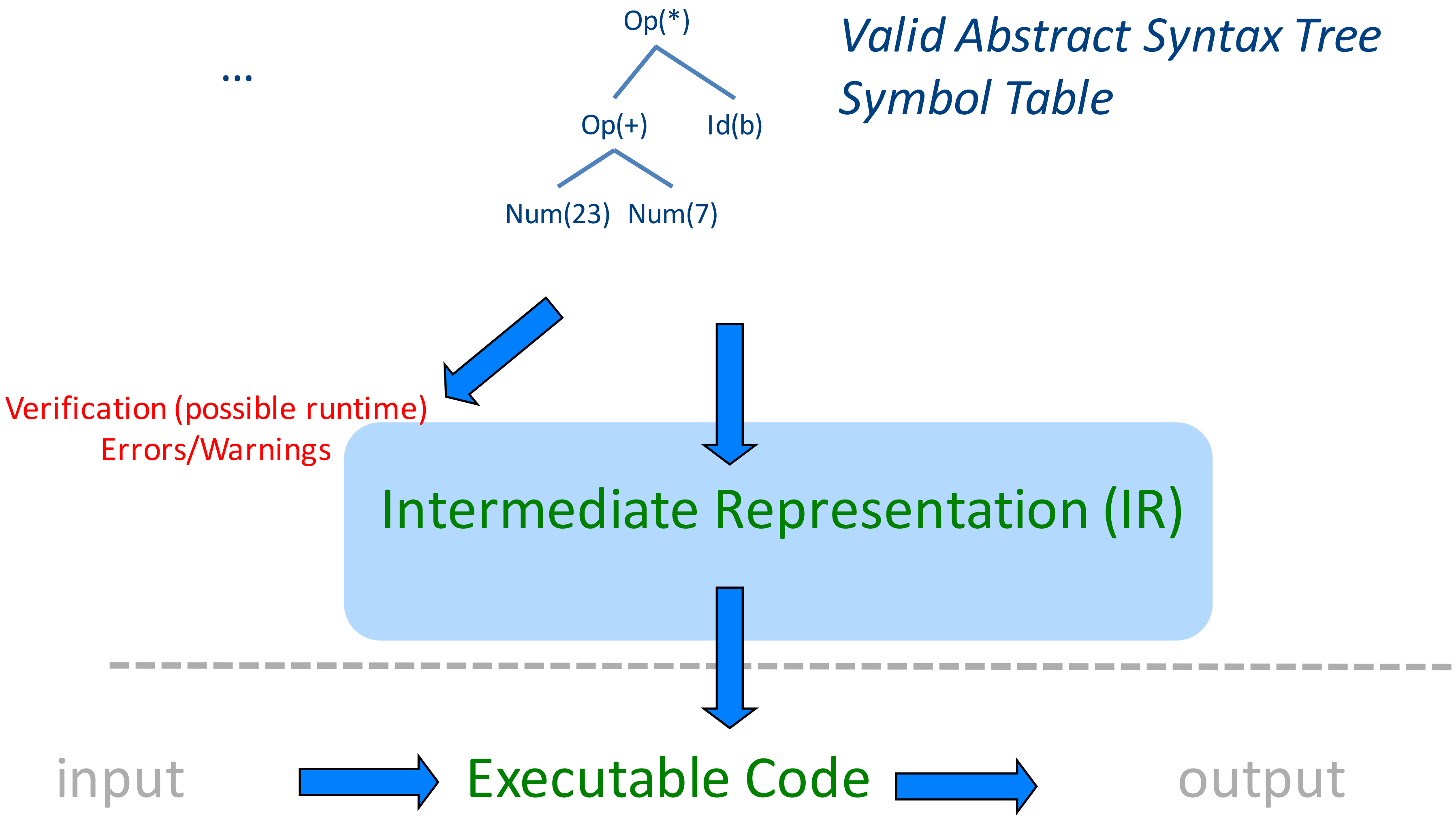
The most common reason for wanting to transform source code is to create an **executable program**.”

A CPU is (a sort of) an ***Interpreter***

> "A **compiler** is a computer program that **transforms** source **code** written in a programming language (source language) into another language (target language).
>
> The most common reason for wanting to transform source code is to create an **executable program**."

- Interprets machine code …
  - Why not AST?
- Do we want to go from AST directly to MC?
  - We can, but …
    - Machine specific
    - Very low level

Code Generation in Stages



...

Op(*)

Op(+) Id(b)

Num(23) Num(7)

Valid Abstract Syntax Tree

Symbol Table

Verification (possible runtime)
Errors/Warnings

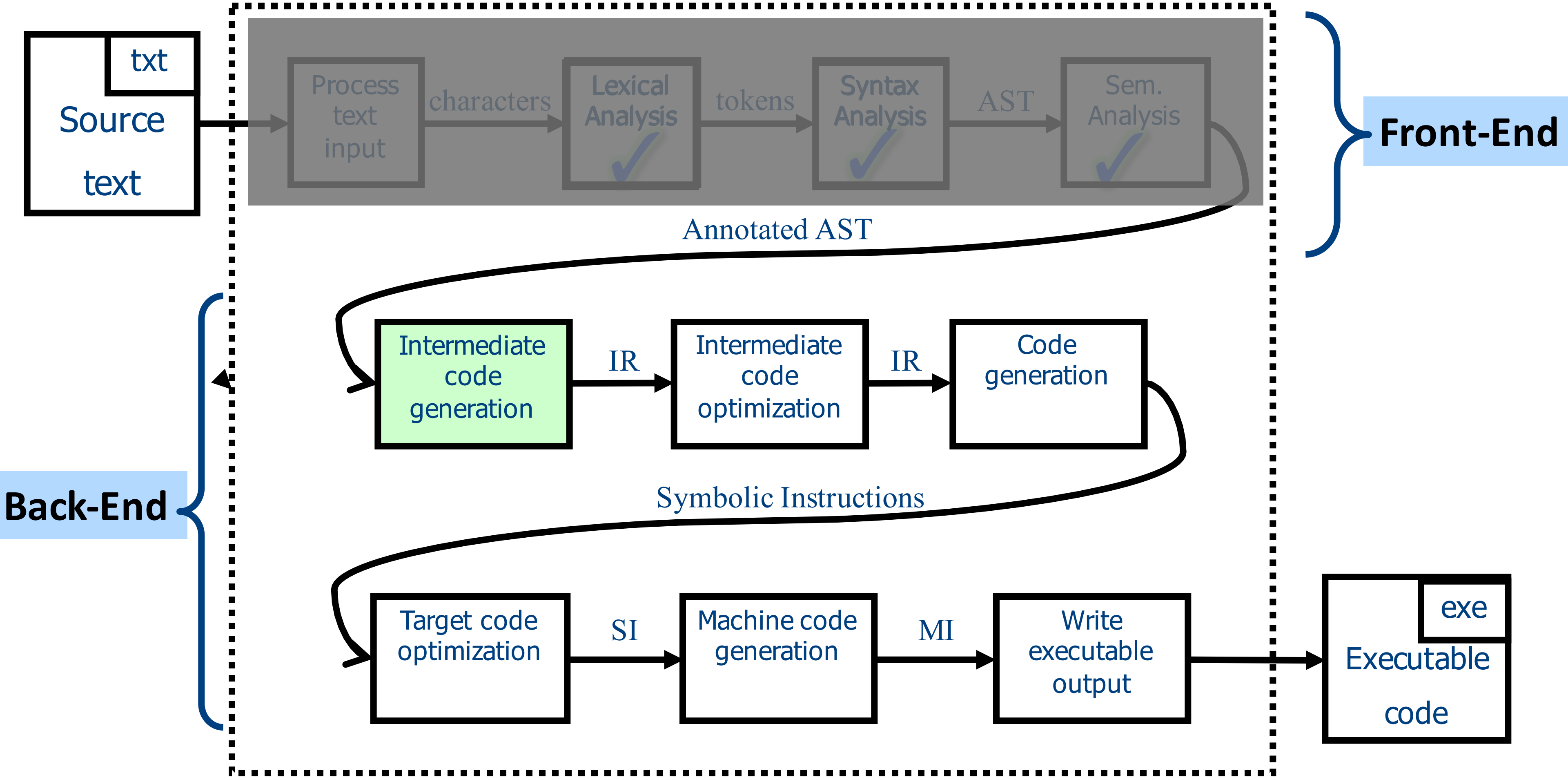
Intermediate Representation (IR)

input

Executable Code

output

Where we are


txt
Source text
Process text input
characters
Lexical Analysis ✓
tokens
Syntax Analysis ✓
AST
Sem. Analysis ✓
Front-End
Annotated AST
Intermediate code generation
IR
Intermediate code optimization
IR
Code generation
Back-End
Symbolic Instructions
Target code optimization
SI
Machine code generation
MI
Write executable output
exe
Executable code

1 Note: Compile Time vs Runtime

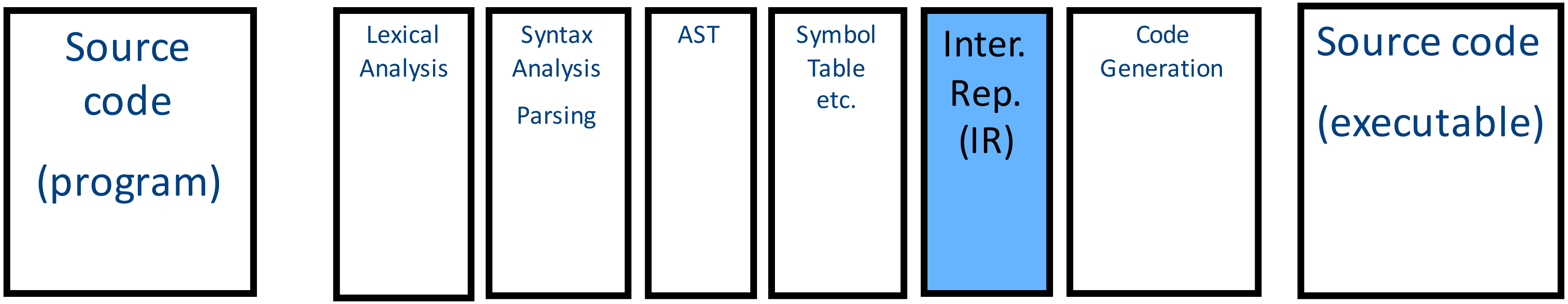
- Compile time: Data structures used during program compilation

- Runtime: Data structures used during program execution
  - Activation record stack
  - Memory management

- The compiler generates code that allows the program to interact with the runtime

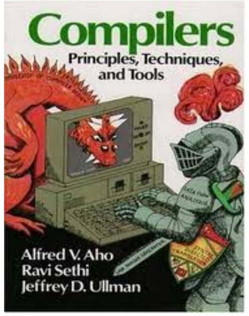
Intermediate Representation

Code Generation: IR



- Translating from abstract syntax (AST) to intermediate representation (IR)
  - Three-**A**ddress **C**ode
- …

Three-**A**ddress **C**ode IR



Chapter 8

- A popular form of IR
- High-level assembly where instructions have at most three operands

IR by example

Sub-expressions example

Source

```
int a;
int b;
int c;
int d;
a = b + c + d;
b = a * a + b * b;
```

IR

```
_t0 = b + c;
a = _t0 + d;
_t1 = a * a;
_t2 = b * b;
b = _t1 + _t2;
```

Sub-expressions example

Source

```
int a;
int b;
int c;
int d;
a = b + c + d;
b = a * a + b * b;
```

LIR (unoptimized)

```
_t0 = b + c;
a = _t0 + d;
_t1 = a * a;
_t2 = b * b;
b = _t1 + _t2;
```

Temporaries explicitly store intermediate values resulting from sub-expressions

Variable assignments

- var = constant ;
- var_1 = var_2 ;
- var_1 = var_2 **op** var_3 ;
- var_1 = constant **op** var_2 ;
- var_1 = var_2 **op** constant ;
- var = constant_1 **op** constant_2 ;
- Permitted operators are **+, -, *, /, %**

In the impl. var is replaced by a pointer to the symbol table

A compiler-generated temporary can be used instead of a var

Booleans

- Boolean variables are represented as integers that have zero or nonzero values
- In addition to the arithmetic operator, TAC supports <, ==, ||, and &&
- How might you compile the following?

```
b = (x <= y);
```

```
_t0 = x < y;
_t1 = x == y;
b = _t0 || _t1;
```

Unary operators

- How might you compile the following assignments from unary statements?

```
y = -x;


z := !w;
```

```
y = 0 - x;
y = -1 * x;


z = w == 0;
```

Control flow instructions

- Label introduction

  ```
  _label_name:
  ```

  Indicates a point in the code that can be jumped to
- Unconditional jump: go to instruction following label L

  ```
  Goto L;
  ```
- Conditional jump: test condition variable t;
  if 0, jump to label L

  ```
  IfZ t Goto L;
  ```
- Similarly : test condition variable t;
  if not zero, jump to label L

  ```
  IfNZ t Goto L;
  ```

Control-flow example – conditions

```
int x;
int y;
int z;

if (x < y)
    z = x;
else
    z = y;
z = z * z;
```

```
          _t0 = x < y;
          IfZ _t0 Goto _L0;
          z = x;
          Goto _L1;
_L0:
          z = y;
_L1:
          z = z * z;
```

Control-flow example – loops

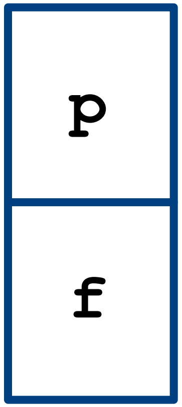
```
int x;
int y;

while (x < y) {
   x = x * 2;
}

y = x;
```

```
_L0:
      _t0 = x < y;
      IfZ _t0 Goto _L1;
      x = x * 2;
      Goto _L0;
_L1:
      y = x;
```

Procedures / Functions

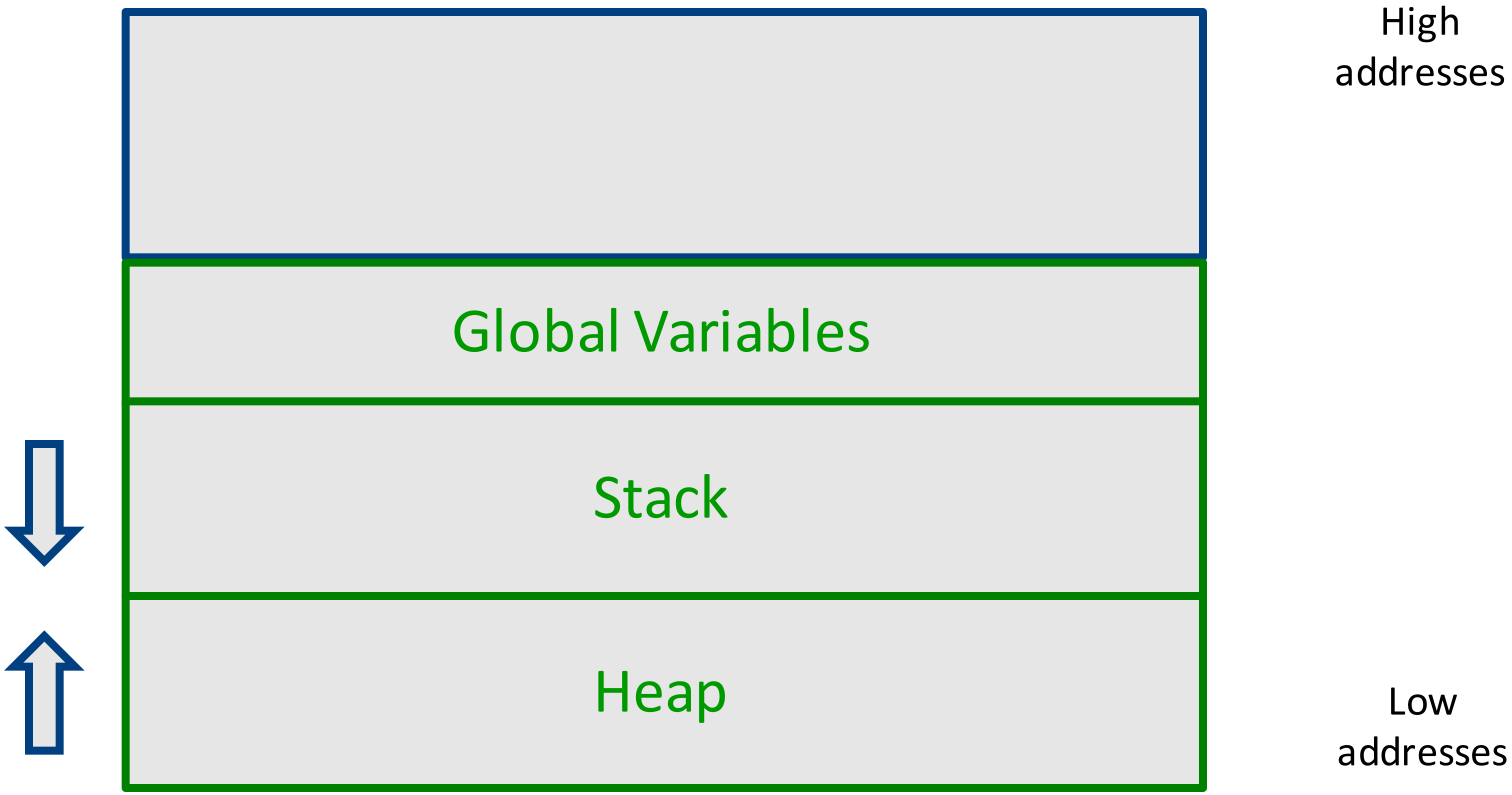
```
p(){
  int y=1, x=0;
  x=f(a_1,…,a_n);
  print(x);
}
```

- What happens in runtime?

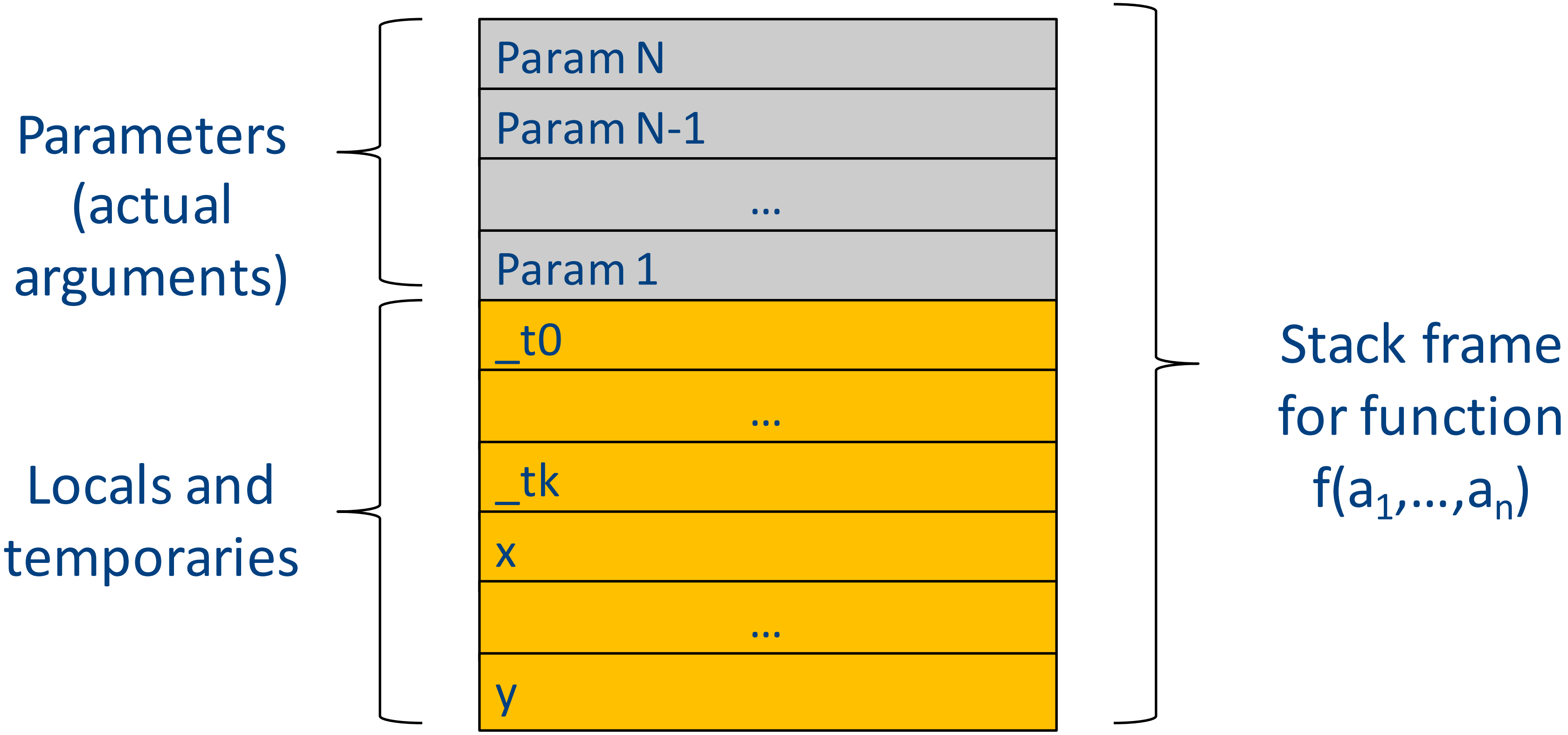


Memory Layout

(popular convention)



A logical stack frame



Parameters (actual arguments)

Param N

Param N-1

…

Param 1

_t0

…

_tk

x

…

y

Locals and temporaries

Stack frame for function $f(a_1,\ldots,a_n)$

Procedures / Functions

- A procedure call instruction **pushes** arguments to stack and **jumps** to the function label
  A statement `x=f(a1,…,an);` looks like

  ```
  Push a1; … Push an;
  Call f;
  Pop x; // pop returned value, and copy to it
  ```

- Returning a value is done by **pushing** it to the stack (`return x;`)

  ```
  Push x;
  ```

- **Return control** to caller (and **roll up stack**)

  ```
  Return;
  ```

Functions example

```
int SimpleFn(int z) {
   int x, y;
   x = x * y * z;
   return x;
}

void main() {
  int w;
  w = SimpleFunction(137);
}
```

```
_SimpleFn:
_t0 = x * y;
_t1 = _t0 * z;
x = _t1;
Push x;
Return;

main:
_t0 = 137;
Push _t0;
Call _SimpleFn;
Pop w;
```

Memory access instructions

- **Copy** instruction: a = b
- **Load/store** instructions:

  a = *b   *a = b
- **Address of** instruction a=&b
- **Array accesses**:

  a = b[i]   a[i] = b
- **Field accesses**:

  a = b[f]   a[f] = b
- **Memory allocation** instruction:

  a = alloc(size)
  - Sometimes left out (e.g., malloc is a procedure in C)

Memory access instructions

- **Copy** instruction: a = b
- **Load/store** instructions:
  a = *b   ***a = b**
- **Address of** instruction a=&b
- **Array accesses**:
  a = b[i]   a[i] = b
- **Field accesses**:
  a = b[f]   a[f] = b
- **Memory allocation** instruction:
  a = alloc(size)
  - Sometimes left out (e.g., malloc is a procedure in C)

Array operations

x := y[i]

```
t1 := &y      ; t1 = address-of y
t2 := t1 + i  ; t2 = address of y[i]
x  := *t2     ; loads the value located at y[i]
```

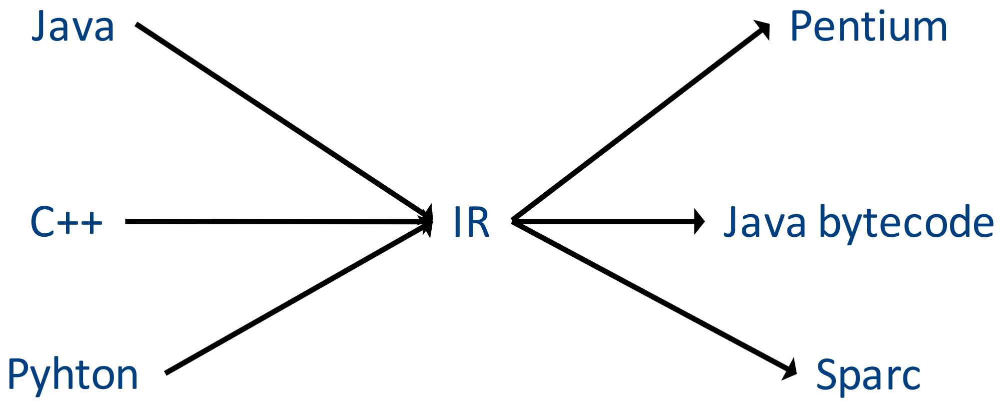
x[i] := y

```
t1   := &x      ; t1 = address-of x
t2   := t1 + i  ; t2 = address of x[i]
*t2 := y        ; store through pointer
```

IR Summary

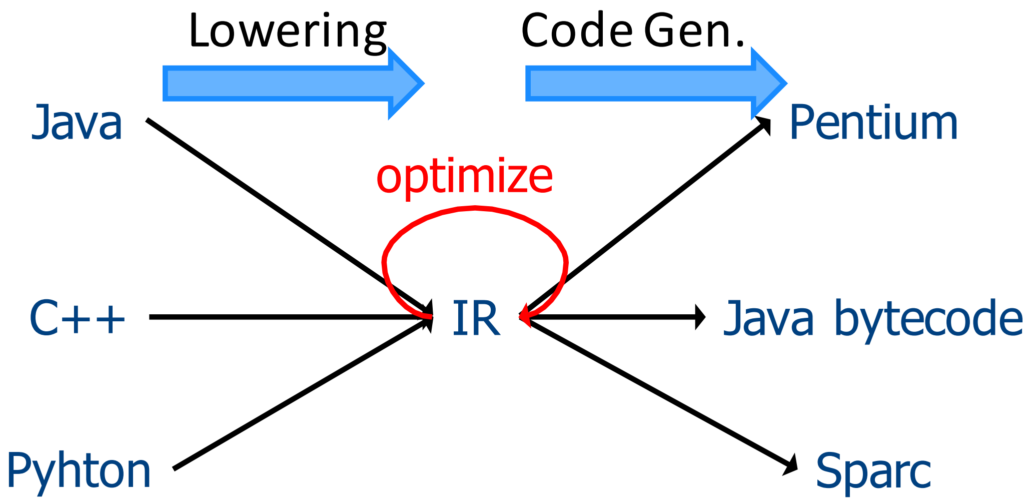
Intermediate representation

- A language that is between the source language and the target language – not specific to any machine
- Goal 1: retargeting compiler components for different source languages/target machines



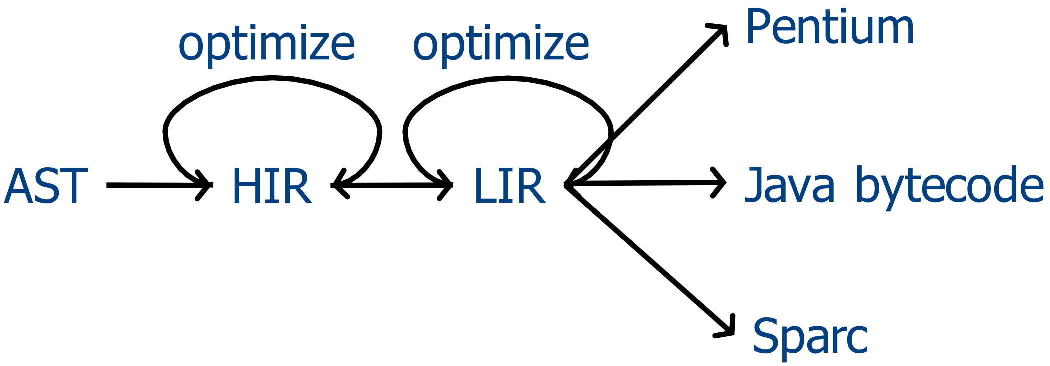
Intermediate representation

- A language that is between the source language and the target language – not specific to any machine
- Goal 1: retargeting compiler components for different source languages/target machines
- Goal 2: machine-independent optimizer
  - Narrow interface: small number of instruction types



Multiple IRs

- Some optimizations require high-level structure
- Others more appropriate on low-level code
- Solution: use multiple IR stages

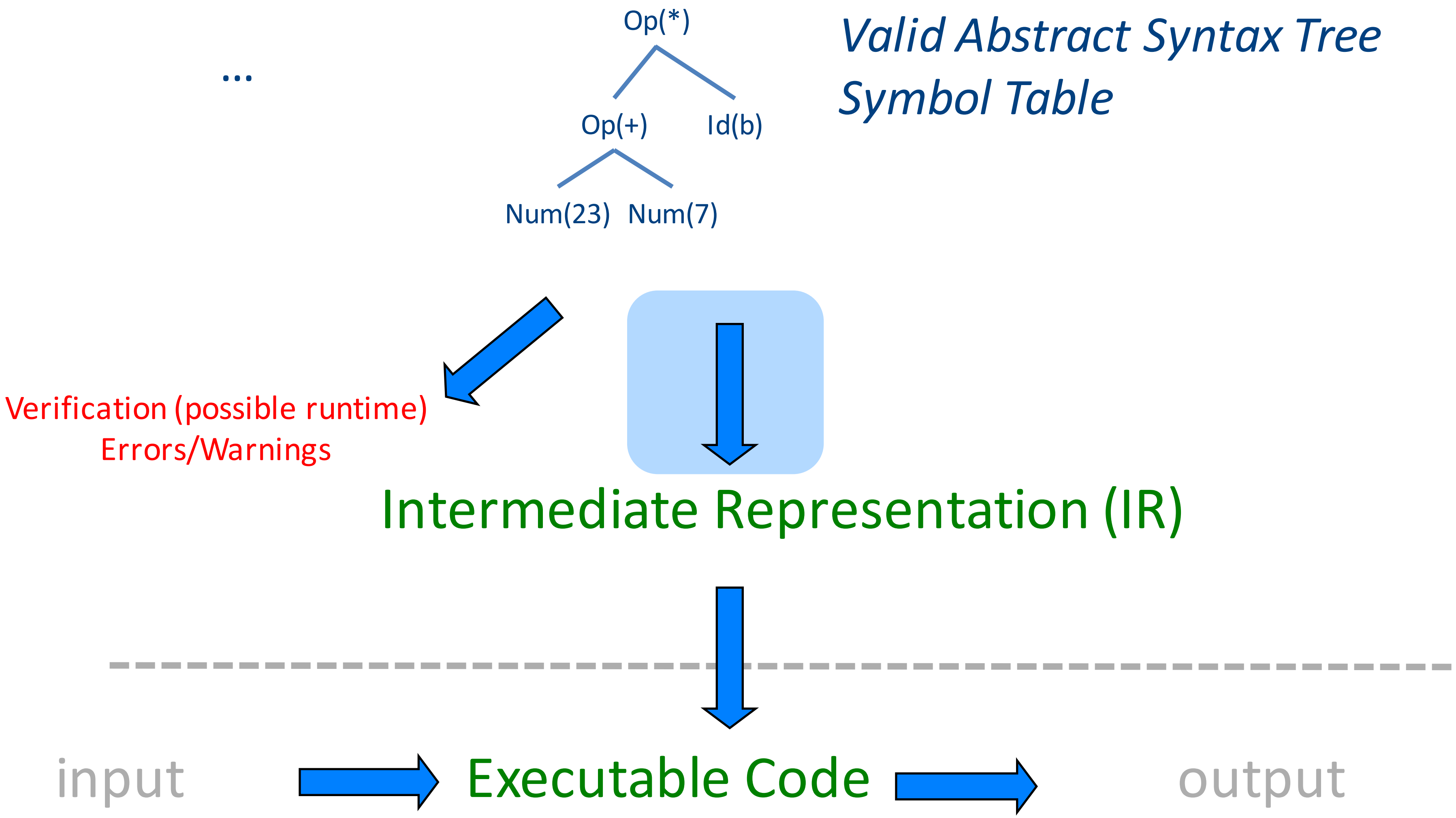


AST vs. LIR for imperative languages

AST	LIR
Rich set of language constructs	An abstract machine language
Rich type system	Very limited type system
Declarations: types (classes, interfaces), functions, variables	Only computation-related code
Control flow statements: if-then-else, while-do, break-continue, switch, exceptions	Labels and conditional/ unconditional jumps, no looping
Data statements: assignments, array access, field access	Data movements, generic memory access statements
Expressions: variables, constants, arithmetic operators, logical operators, function calls	No sub-expressions, logical as numeric, temporaries, constants, function calls – explicit argument passing

Lowering AST to TAC

IR Generation



…

Valid Abstract Syntax Tree

Symbol Table

Verification (possible runtime)
Errors/Warnings

Intermediate Representation (IR)

input

Executable Code

output

TAC generation

- At this stage in compilation, we have
  - an AST
  - annotated with scope information
  - and annotated with type information
- To generate TAC for the program, we do recursive tree traversal
  - Generate TAC for any subexpressions or substatements
  - Using the result, generate TAC for the overall expression

TAC generation for expressions

- Define a function **cgen**(*expr) that generates* TAC that computes an expression, stores it in a temporary variable, then hands back the name of that temporary
  - Define **cgen** directly for atomic expressions (constants, this, identifiers, etc.)
- Define **cgen** recursively for compound expressions (binary operators, function calls, etc.)

cgen for basic expressions

```
cgen(k) = { // k is a constant
    Choose a new temporary t
    Emit( t = k )
    Return t
}

cgen(id) = { // id is an identifier
    Choose a new temporary t
    Emit( t = id )
    Return t
}
```

cgen for binary operators

```
cgen($e_1 + e_2$) = {
    Choose a new temporary $t$
    Let $t_1$ = cgen($e_1$)
    Let $t_2$ = cgen($e_2$)
    Emit( $t = t_1 + t_2$ )
    Return $t$
}
```

cgen example

```
cgen(5 + x) = {
    Choose a new temporary $t$
    Let $t_1$ = cgen(5)
    Let $t_2$ = cgen(x)
    Emit( $t = t_1 + t_2$ )
    Return $t$
}
```

cgen example

```
cgen(5 + x) = {
    Choose a new temporary $t$
    Let $t_1 = \{$
        Choose a new temporary $t$
        Emit( $t = 5;$ )
        Return $t$
    }
    Let $t_2$ = cgen(x)
    Emit( $t = t_1 + t_2$ )
    Return $t$
}
```

cgen example

```
**cgen**(5 + x) = {
    Choose a new temporary $t$
    Let $t_1$ = {
        Choose a new temporary $t$
        Emit( $t = 5;$ )
        Return $t$
    }
    Let $t_2$ = {
        Choose a new temporary $t$
        Emit( $t = x;$ )
        Return $t$
    }
    Emit( $t = t_1 + t_2;$ )
    Return $t$
}
```

Returns an **arbitrary fresh** name

```
t1 = 5;
t2 = x;
t = t1 + t2;
```

cgen example

```
**cgen**(5 + x) = {
    Choose a new temporary $t$
    Let $t_1$ = {
        Choose a new temporary $t$
        Emit( $t = 5;$ )
        Return $t$
    }
    Let $t_2$ = {
        Choose a new temporary $t$
        Emit( $t = x;$ )
        Return $t$
    }
    Emit( $t = t_1 + t_2;$ )
    Return $t$
}
```

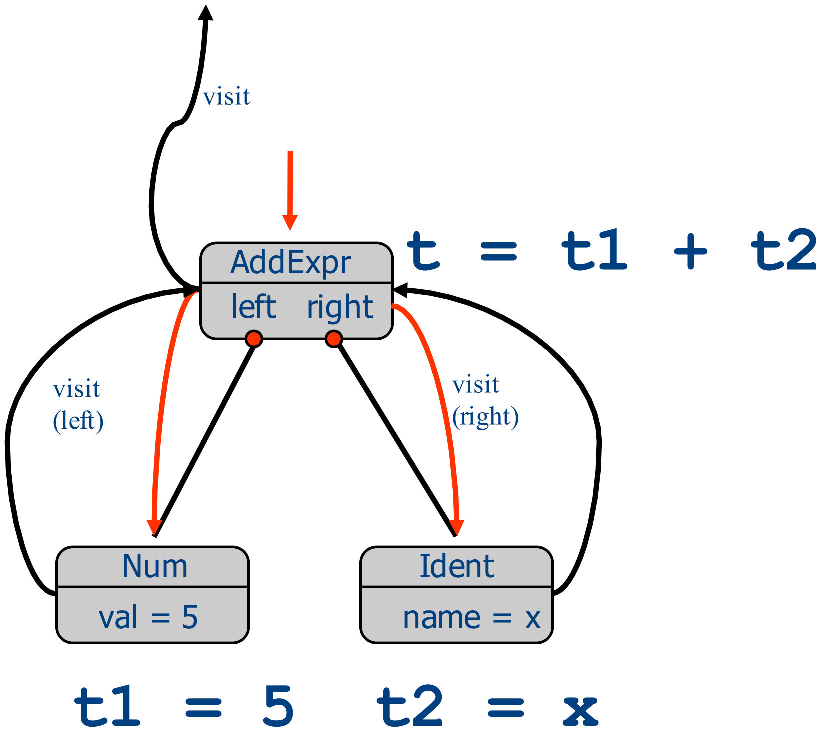
Returns an **arbitrary fresh** name

```
_t18 = 5;
_t29 = x;
_t6 = _t18 + _t29;
```

Inefficient translation, but we will improve this later

cgen as recursive AST traversal

cgen(5 + x)



```
t = t1 + t2
```

```
t1 = 5   t2 = x
```

```
t1 = 5;

t2 = x;

t = t1 + t2;
```

Naive **cgen** for expressions

- Maintain a counter for temporaries in c
- Initially: c = 0
- **cgen**(e_1 *op* e_2) = {

```
    Let A = cgen(e_1)
    c = c + 1
    Let B = cgen(e_2)
    c = c + 1
    Emit( _tc = A op B; )
    Return _tc
}
```

Example

cgen((a*b)-d)

Example

c = 0

cgen((a*b)-d)

Example

```
c = 0
cgen( (a*b)-d) = {
    Let A = cgen(a*b)
    c = c + 1
    Let B = cgen(d)
    c = c + 1
    Emit( _tc = A - B; )
    Return _tc
}
```

Example

```
c = 0
cgen( (a*b)-d) = {
  Let A = {
      Let A = cgen(a)
      c = c + 1
      Let B = cgen(b)
      c = c + 1
      Emit( _tc = A * B; )
      Return tc
  }
  c = c + 1
  Let B = cgen(d)
  c = c + 1
  Emit( _tc = A - B; )
  Return _tc
}
```

Example

```
c = 0
cgen( (a*b)-d) = {
  Let A = {
      Let A = { Emit(_tc = a;), return _tc }
      c = c + 1
      Let B = { Emit(_tc = b;), return _tc }
      c = c + 1
      Emit( _tc = A * B; )
      Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t0

Code

Example

```
c = 0
cgen( (a*b)-d) = {
   Let A = {
      Let A = { Emit(_tc = a;), return _tc }
      c = c + 1
      Let B = { Emit(_tc = b;), return _tc }
      c = c + 1
      Emit( _tc = A * B; )
      Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t0

Code

```
_t0=a;
```

Example

```
c = 0
cgen( (a*b)-d) = {
   Let A = {
      Let A = { Emit(_tc = a;), return _tc }
      c = c + 1
      Let B = { Emit(_tc = b;), return _tc }
      c = c + 1
      Emit( _tc = A * B; )
      Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t0

Code

```
_t0=a;
_t1=b;
```

Example

```
c = 0
cgen( (a*b)-d) = {
   Let A = {
      Let A = { Emit(_tc = a;), return _tc }
      c = c + 1
      Let B = { Emit(_tc = b;), return _tc }
      c = c + 1
      Emit( _tc = A * B; )
      Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t0

```
Code
_t0=a;
_t1=b;
_t2=_t0*_t1
```

Example

```
c = 0
cgen( (a*b)-d) = {
   Let A = {
      Let A = { Emit(_tc = a;), return _tc }
       c = c + 1
       Let B = { Emit(_tc = b;), return _tc }
       c = c + 1
       Emit( _tc = A * B; )
       Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t2

here A=_t0

Code

```
_t0=a;
_t1=b;
_t2=_t0*_t1
```

Example

```
c = 0
cgen( (a*b)-d) = {
 Let A = {
   Let A = { Emit(_tc = a;), return _tc }
     c = c + 1
     Let B = { Emit(_tc = b;), return _tc }
     c = c + 1
     Emit( _tc = A * B; )
     Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t2

here A=_t0

Code

```
_t0=a;
_t1=b;
_t2=_t0*_t1
_t3=d;
```

Example

```
c = 0
cgen( (a*b)-d) = {
 Let A = {
    Let A = { Emit(_tc = a;), return _tc }
      c = c + 1
      Let B = { Emit(_tc = b;), return _tc }
      c = c + 1
      Emit( _tc = A * B; )
      Return _tc
   }
   c = c + 1
   Let B = { Emit(_tc = d;), return _tc }
   c = c + 1
   Emit( _tc = A - B; )
   Return _tc
}
```

here A=_t2

here A=_t0

Code

```
_t0=a;
_t1=b;
_t2=_t0*_t1
_t3=d;
_t4=_t2-_t3
```

cgen for short-circuit disjunction

cgen(e1 || e2)

```
Emit(_t1 = 0; _t2 = 0;)
Let $L_{after}$ be a new label
Let _t1 = cgen(e1)
Emit( IfNZ _t1 Goto $L_{after}$)
Let _t2 = cgen(e2)
Emit( $L_{after}$: )
Emit( _t = _t1 || _t2; )
Return _t
```

cgen for statements

- We can extend the **cgen** function to operate over statements as well
- Unlike **cgen** for expressions, **cgen** for statements does not return the name of a temporary holding a value.
  - *(Why?)*

cgen for simple statements

```
cgen(expr;) = {
    cgen(expr)
}
```

cgen for `if-then-else`

cgen(if (e) s_1 else s_2)

```
Let _t = cgen(e)
Let $L_{true}$ be a new label
Let $L_{false}$ be a new label
Let $L_{after}$ be a new label
Emit( IfZ _t Goto $L_{false}$; )
cgen($s_1$)
Emit( Goto $L_{after}$; )
Emit( $L_{false}$: )
cgen($s_2$)
Emit( Goto $L_{after}$;)
Emit( $L_{after}$: )
```

cgen for **`while`** loops

cgen(while *(expr) stmt)*

```
Let $L_{before}$ be a new label.
Let $L_{after}$ be a new label.
Emit( $L_{before}$: )
Let t = cgen(expr)
Emit( IfZ t Goto Lafter; )
cgen(stmt)
Emit( Goto $L_{before}$; )
Emit( $L_{after}$: )
```

Our first optimization

Naive **cgen** for expressions

- Maintain a counter for temporaries in c
- Initially: c = 0
- cgen definition:

```
cgen($e_1$ op $e_2$) = {
    Let A = cgen($e_1$)
    c = c + 1
    Let B = cgen($e_2$)
    c = c + 1
    Emit( _tc = A op B; )
    Return _tc
}
```

Naïve translation

- **cgen** translation shown so far very inefficient
  - Generates (too) many temporaries – one per sub-expression
  - Generates many instructions – at least one per sub-expression
- Expensive in terms of running time and space
- Code bloat

- We can do much better …

Naive **cgen** for expressions

- Maintain a counter for temporaries in c
- Initially: c = 0
- **cgen**(e_1 *op* e_2) = {

```
    Let A = cgen(e_1)
    c = c + 1
    Let B = cgen(e_2)
    c = c + 1
    Emit( _tc = A op B; )
    Return _tc
}
```

- **Observation: temporaries in cgen(e_1) can be reused in cgen(e_2)**

Improving **cgen** for expressions

- Observation – naïve translation needlessly generates temporaries for leaf expressions
- **Observation – temporaries used exactly once**
  - **Once a temporary has been read it can be reused for another sub-expression**
- **cgen**(e_1 *op* e_2) = {

```
    Let _t1 = cgen(e_1)
    Let _t2 = cgen(e_2)
    Emit( _t =_t1 op _t2; )
    Return t
}
```

- Temporaries **cgen**(e_1) can be reused in **cgen**(e_2)

Sethi-Ullman translation

- Algorithm by Ravi Sethi and Jeffrey D. Ullman to emit optimal TAC
  - Minimizes number of temporaries
- Main data structure in algorithm is a stack of temporaries
  - Stack corresponds to recursive invocations of _t = **cgen**(e)
  - All the temporaries on the stack are live
    - Live = contain a value that is needed later on

Live temporaries stack

- Implementation: use counter c to implement live temporaries stack
  - Temporaries _t(0), … , _t(c) are alive
  - Temporaries _t(c+1), _t(c+2)… can be reused
  - Push means increment c, pop means decrement c
- In the translation of _t(c)=**cgen**(e_1 *op* e_2)

```
_t(c) = cgen(e1)
              --------------- c = c + 1
_t(c) = cgen(e2)
              --------------- c = c - 1
_t(c) = _t(c) op  _t(c+1)
```

Using stack of temporaries example

_t0 = **cgen**(((c*d)-(e*f))+(a*b))

```
                  ------- c = 0

                              _t0 = c*d
                                          ------- c = c + 1
_t0 = cgen(c*d)-(e*f))        _t1 = e*f
                                          ------- c = c - 1
                              _t0 = _t0 -_t1

                  ------- c = c + 1
 _t1 = a*b

                  ------- c = c - 1

 _t0 = _t0 + _t1
```

Temporaries

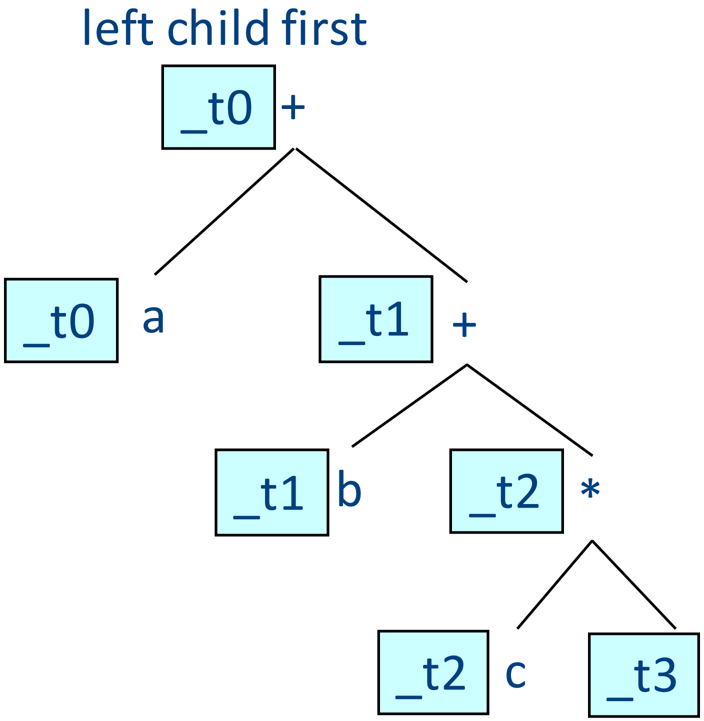
Weighted register allocation

- Suppose we have expression e_1 *op* e_2
  - e_1, e_2 without side-effects
    - That is, no function calls, memory accesses, ++x
  - **cgen**(e_1 *op* e_2) = **cgen**(e_2 *op* e_1)
  - *Does order of translation matter?*
- Sethi & Ullman’s algorithm translates heavier sub-tree first
  - Optimal local (per-statement) allocation for side-effect-free statements

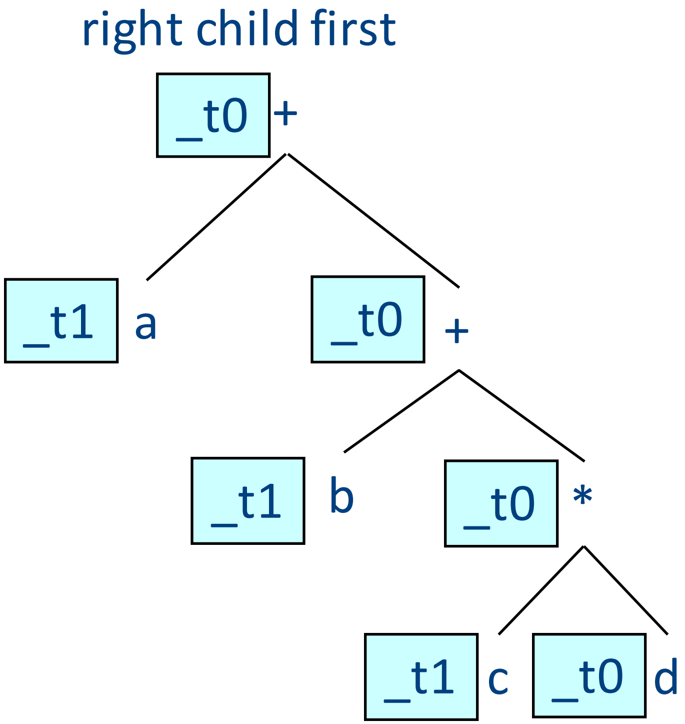
Example

_t0 = **cgen**(a+(b+(c*d)))

*+ and * are commutative operators*



4 temporaries



2 temporary

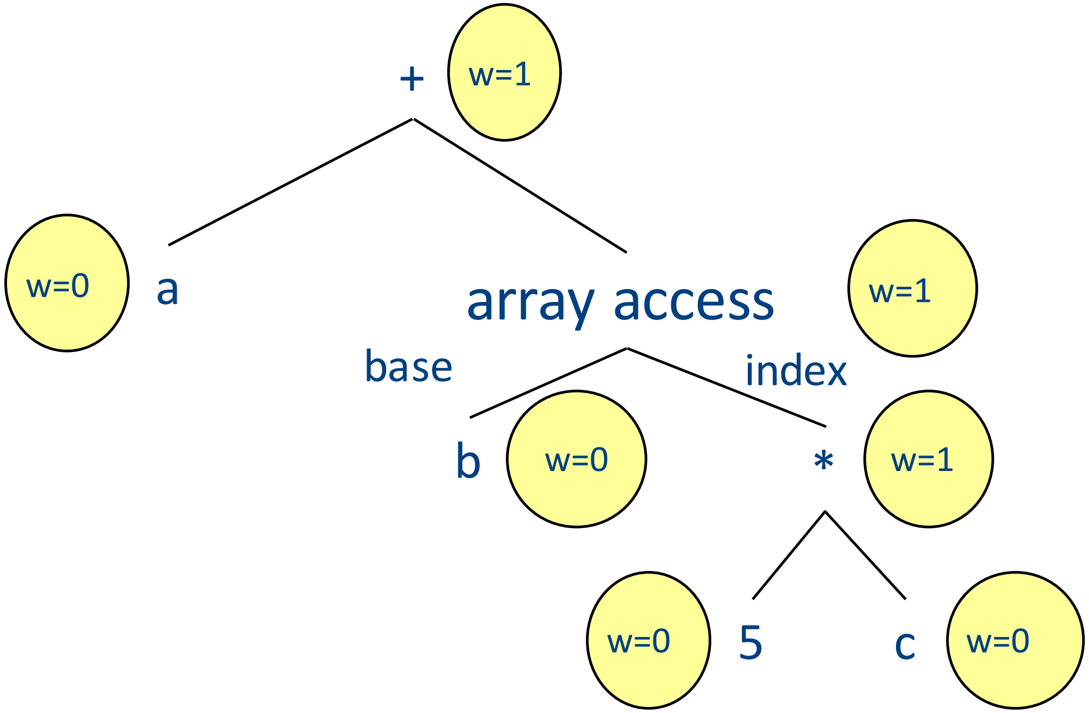
Weighted register allocation

- Can save registers by **re-ordering** subtree **computations**
- Label each node with its **weight**
  - Weight = number of registers needed
  - Leaf weight known
  - Internal node weight
    - w(left) > w(right) then w = left
    - w(right) > w(left) then w = right
    - w(right) = w(left) then w = left + 1
- Choose **heavier** child as first to be translated
- WARNING: have to check that no side-effects exist before attempting to apply this optimization
  - pre-pass on the tree

Weighted reg. alloc. example

_t0 = **cgen**(a+b[5*c])

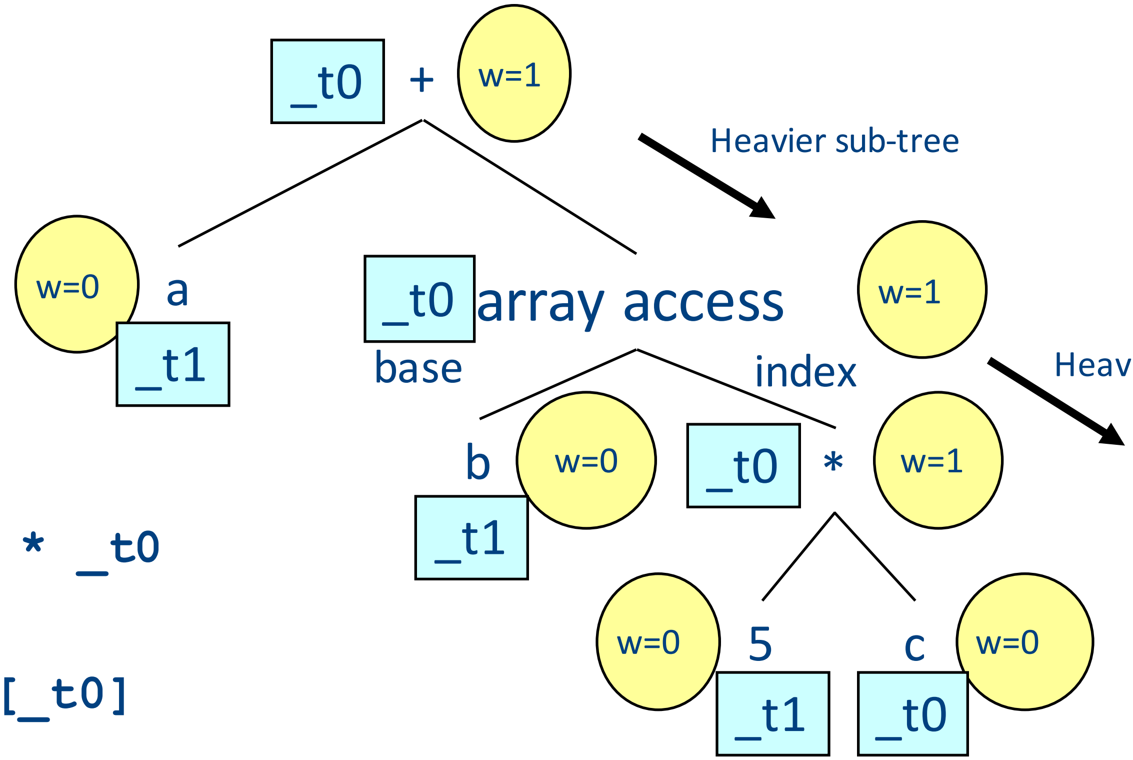
Phase 1: - check absence of side-effects in expression tree
- assign weight to each AST node



Weighted reg. alloc. example

_t0 = **cgen**(a+b[5*c])

Phase 2: - use weights to decide on order of translation



```
_t0 = c
_t1 = 5
_t0 = _t1 * _t0
_t1 = b
_t0 = _t1[_t0]
_t1 = a
_t0 = _t1 + _t0
```

Note on weighted register allocation

- **Must** reset temporaries counter after every statement: x=y; y=z
  - should **not** be translated to

```
_t0 = y;
x = _t0;
_t1 = z;
y = _t1;
```

  - But rather to

```
_t0 = y;
x = _t0;  # Finished translating statement. Set c=0
_t0 = z;
y= _t0;
```

Code generation for procedure calls (+ a few words on the runtime system)

Code generation for procedure calls

- Compile time generation of code for procedure invocations

- Activation Records (aka Stack Frames)

Supporting Procedures

- **Stack**: a new computing environment
  - e.g., temporary memory for **local variables**
- Passing information into the new environment
  - **Parameters**
- **Transfer** of **control** to/from procedure
- Handling return values

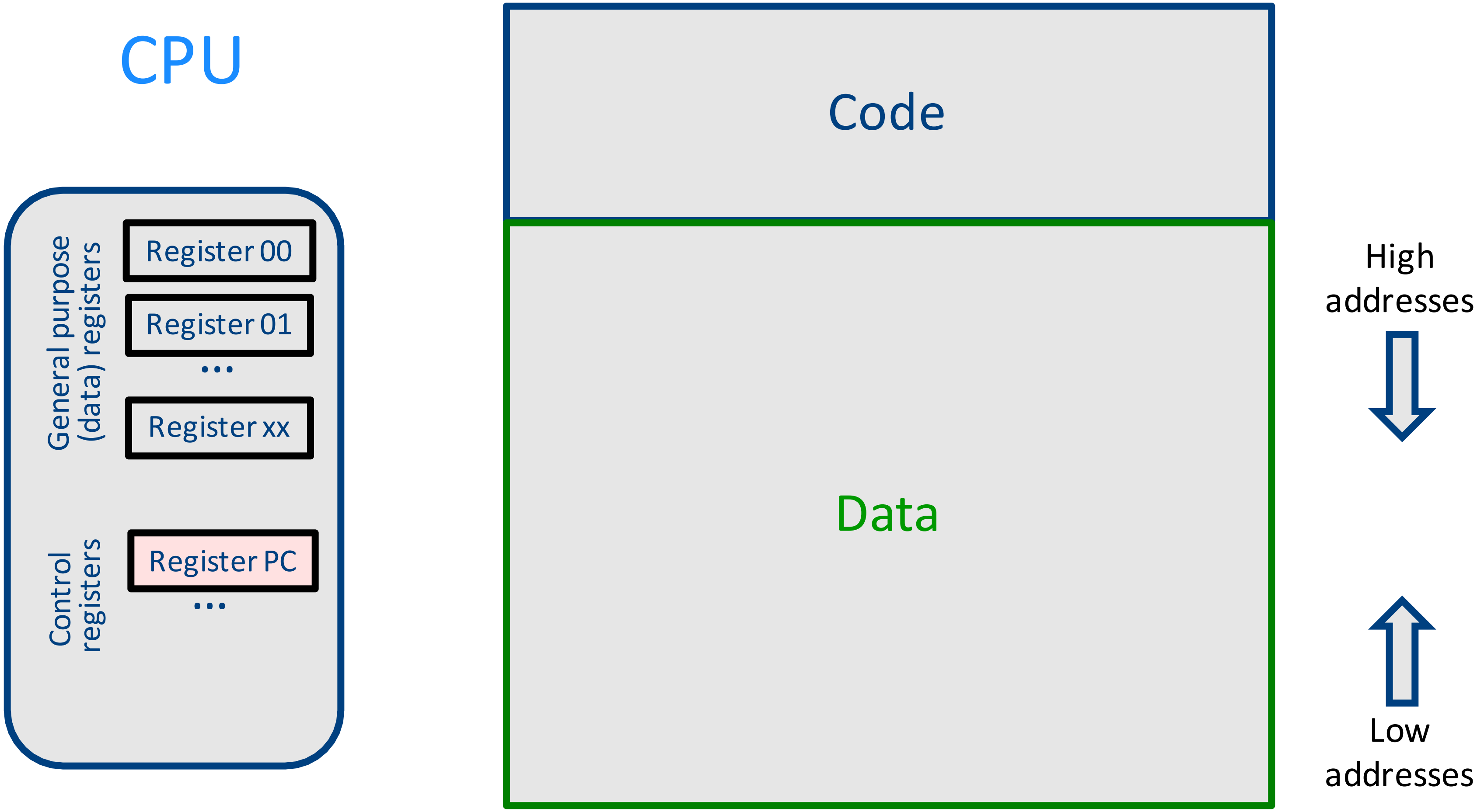
Calling Conventions

- In general, compiler can use any convention to handle procedures

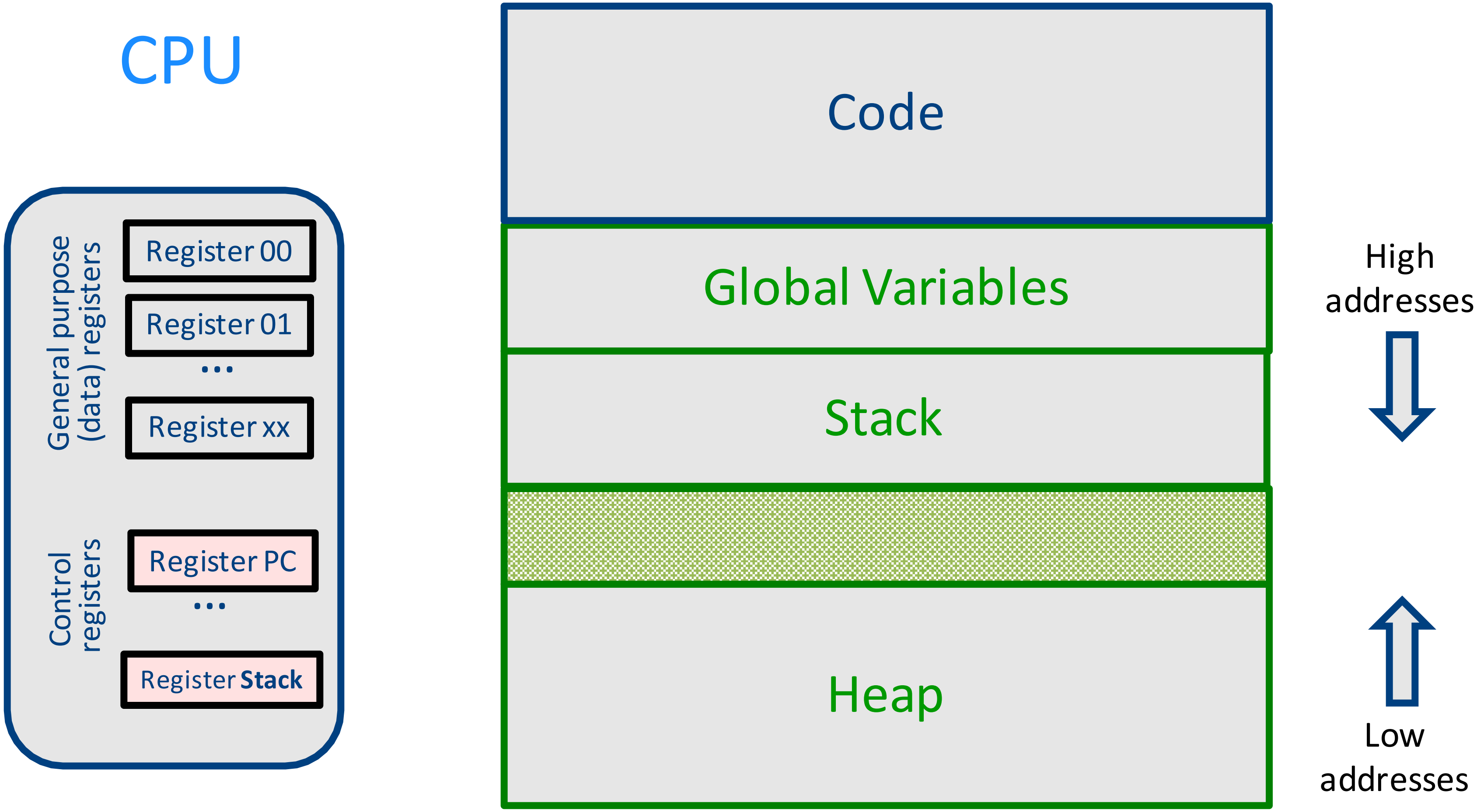
- In practice, CPUs specify standards
    - Aka calling conventios
  - Allows for compiler interoperability
    - Libraries!

Abstract Register Machine

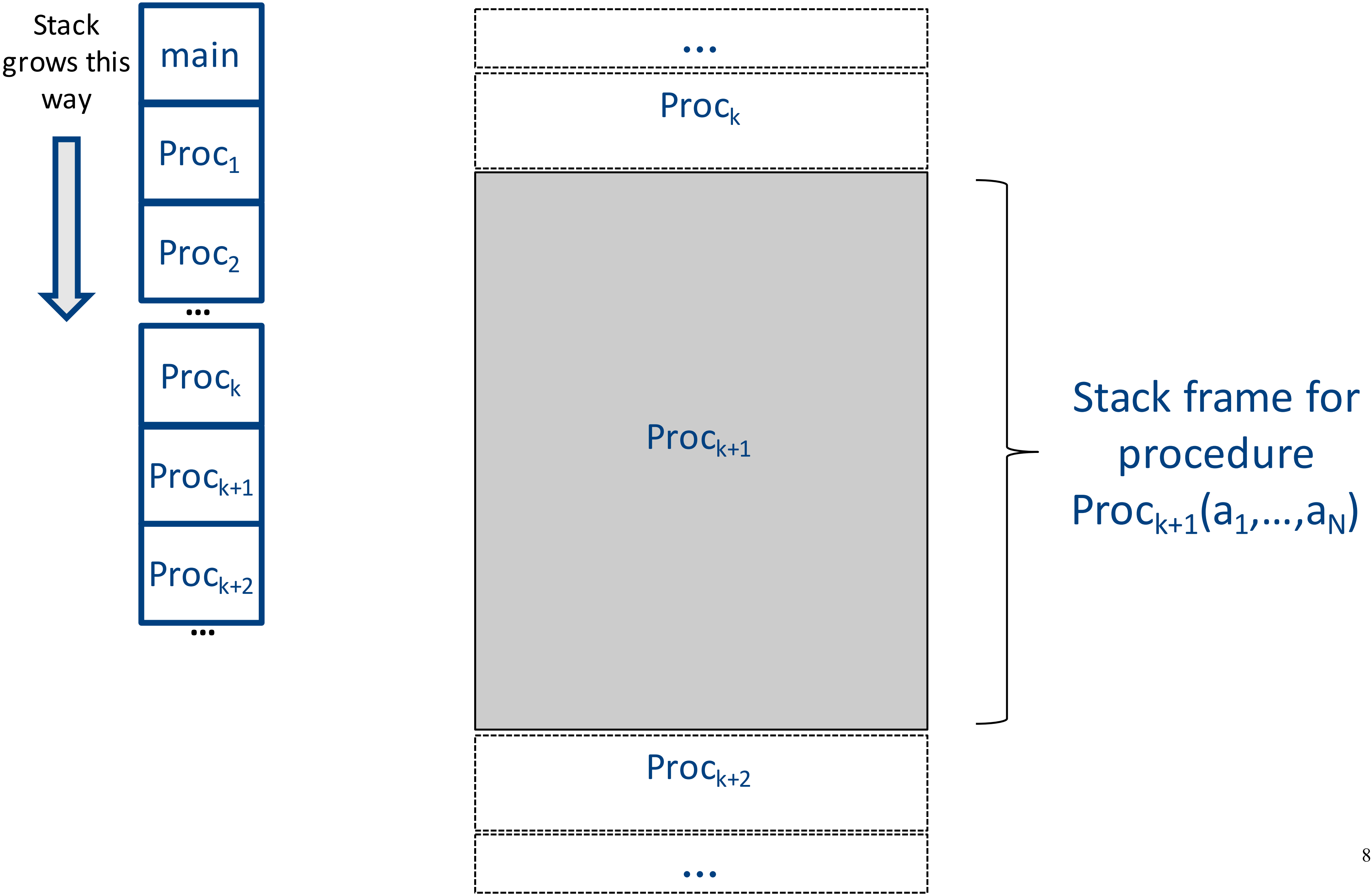
(High Level View)



Abstract Register Machine
(High Level View)

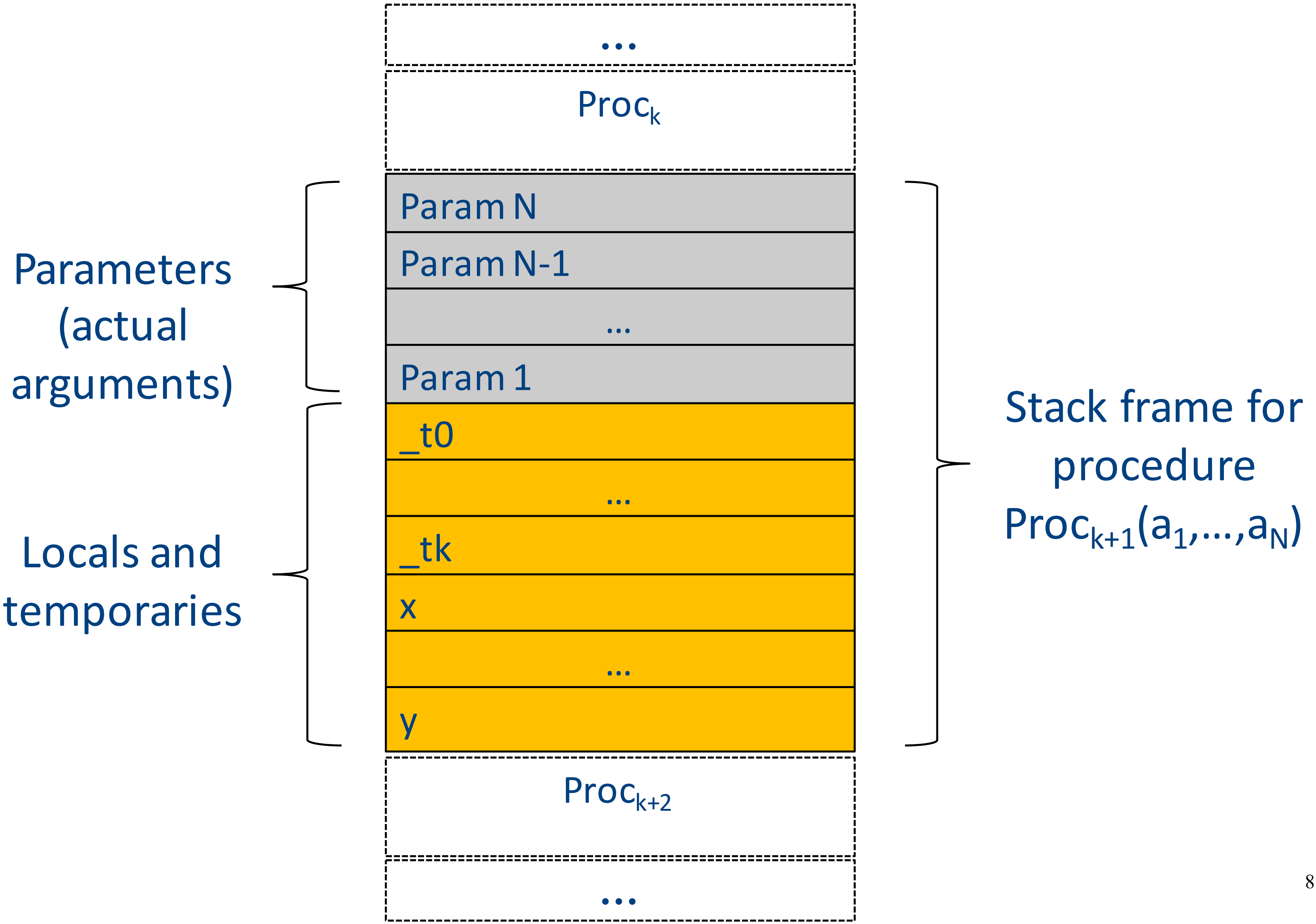


Abstract Activation Record Stack



Stack frame for procedure $\text{Proc}_{k+1}(a_1,\ldots,a_N)$

Abstract Stack Frame



…

Proc_k

Param N

Param N-1

…

Param 1

_t0

…

_tk

x

…

y

Proc_{k+2}

…

Parameters (actual arguments)

Locals and temporaries

Stack frame for procedure $\text{Proc}_{k+1}(a_1,…,a_N)$

Handling Procedures

- Store local variables/temporaries in a stack
- A function call instruction pushes arguments to stack and jumps to the function label
  A statement **`x=f(a1,…,an);`** looks like

  ```
      Push a1; … Push an;
      Call f;
      Pop x; // copy returned value
  ```

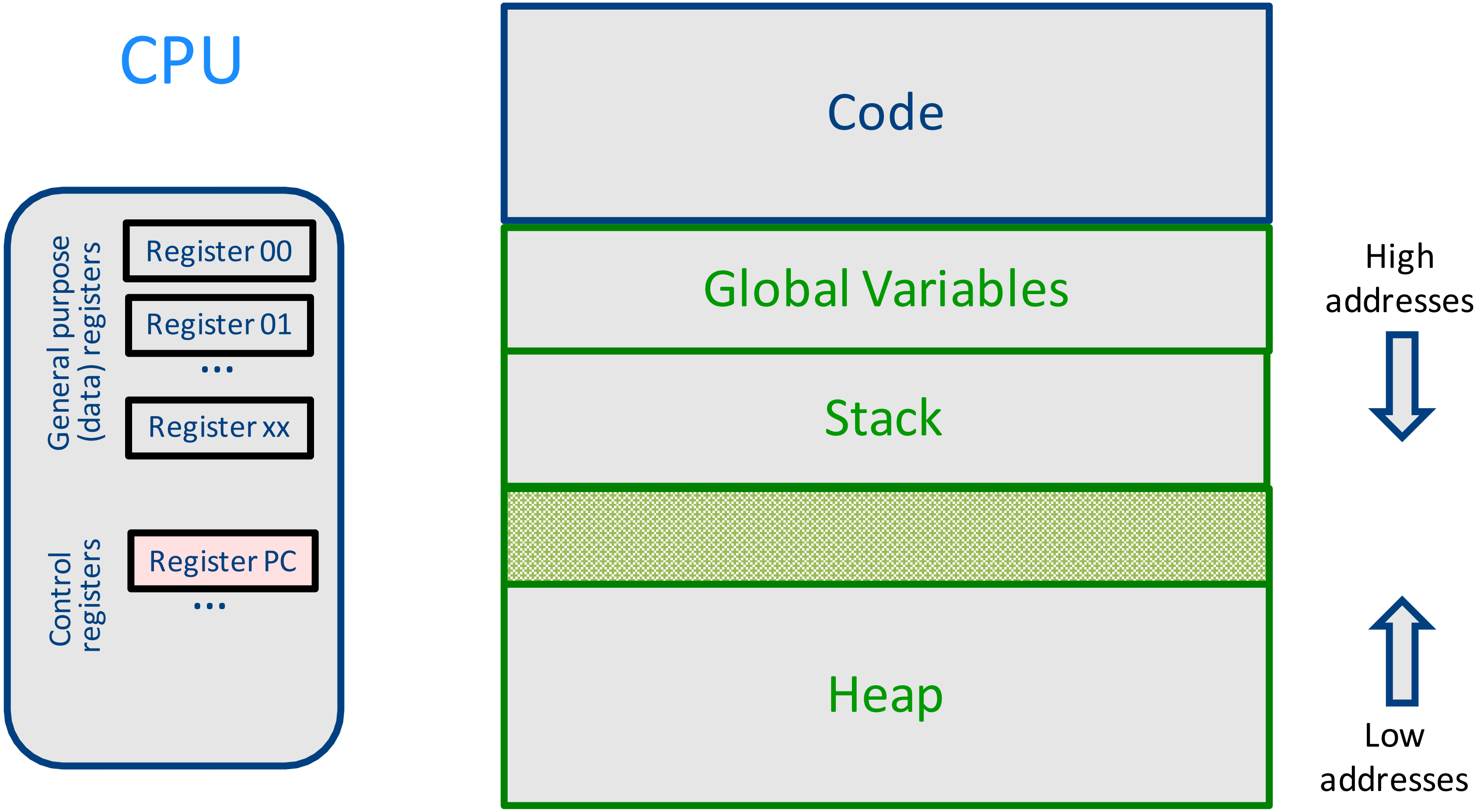
- Returning a value is done by pushing it to the stack (**`return x;`**)

  ```
      Push x;
  ```

- Return control to caller (and roll up stack)

  ```
      Return;
  ```

Abstract Register Machine



CPU

General purpose (data) registers

Register 00

Register 01

…

Register xx

Control registers

Register PC

…

Code

Global Variables

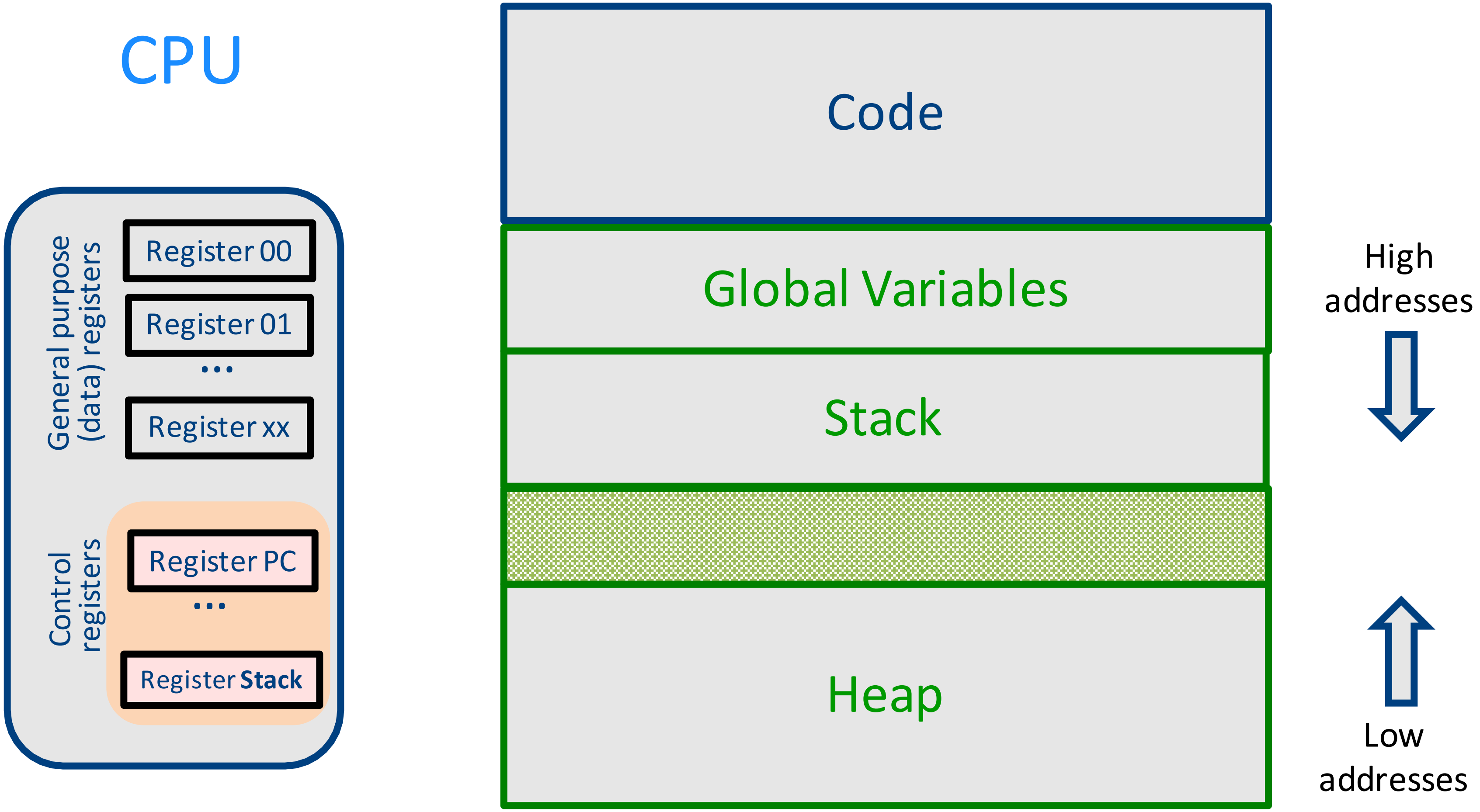
Stack

Heap

High addresses

Low addresses

Abstract Register Machine



Intro: Functions Example

```
int SimpleFn(int z) {
   int x, y;
   x = x * y * z;
   return x;
}

void main() {
  int w;
  w = SimpleFunction(137);
}
```

```
_SimpleFn:
_t0 = x * y;
_t1 = _t0 * z;
x = _t1;
Push x;
Return;

main:
_t0 = 137;
Push _t0;
Call _SimpleFn;
Pop w;
```

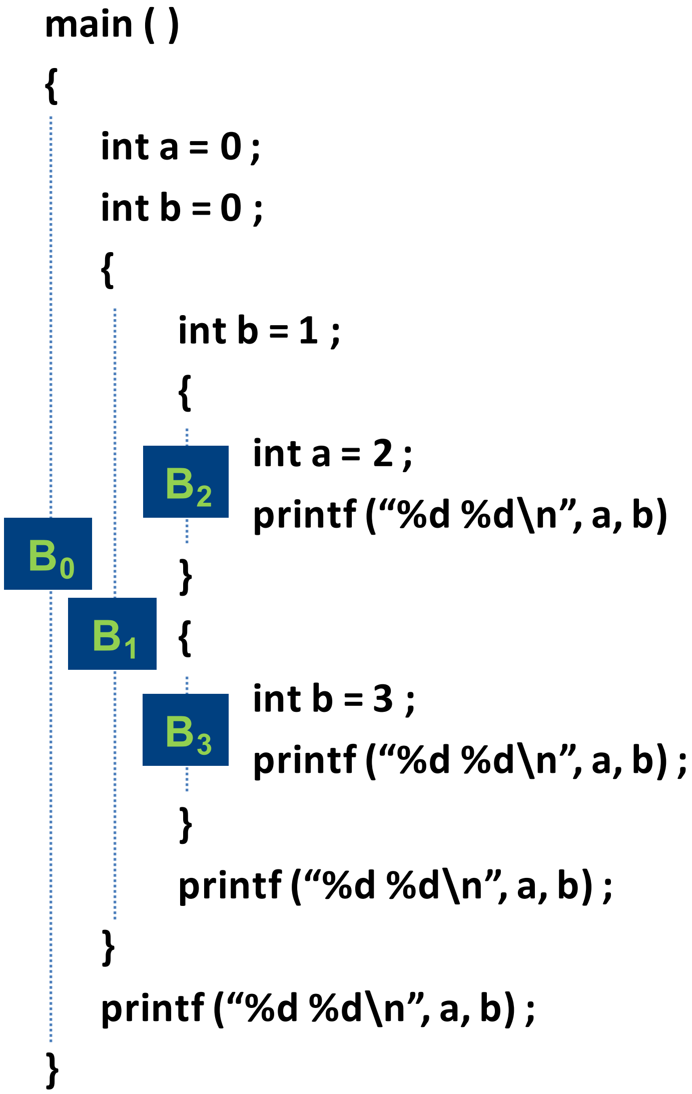
What Can We Do with Procedures?

- Declarations & Definitions
- Call & Return
- Jumping out of procedures
- Passing & Returning procedures as parameters

Design Decisions

- Scoping rules
  - Static scoping vs. dynamic scoping
- Caller/callee conventions
  - Parameters
  - Who saves register values?
- Allocating space for local variables

Static (lexical) Scoping



```
main ( )
{
    int a = 0 ;
    int b = 0 ;
    {
        int b = 1 ;
        {
            int a = 2 ;
            printf (“%d %d\n”, a, b)
        }
        {
            int b = 3 ;
            printf (“%d %d\n”, a, b) ;
        }
        printf (“%d %d\n”, a, b) ;
    }
    printf (“%d %d\n”, a, b) ;
}
```

a name refers to its (closest) enclosing scope

known at compile time

Declaration	Scopes
a=0	B0,B1,B3
b=0	B0
b=1	B1,B2
a=2	B2
b=3	B3

Dynamic Scoping

- Each identifier is associated with a global stack of bindings
- When entering scope where identifier is declared
  - push declaration on identifier stack
- When exiting scope where identifier is declared
  - pop identifier stack
- **Evaluating the identifier in any context binds to the current top of stack**
- Determined **at runtime**

Example

```
int x = 42;

int f() { return x; }
int g() { int x = 1; return f(); }
int main() { return g(); }
```

- What value is returned from main?
- Static scoping?
- Dynamic scoping?

Why do we care?

- We need to generate code to access variables

- Static scoping
  - Identifier binding is known at compile time
  - “Address” of the variable is known at compile time
  - Assigning addresses to variables is part of code generation
  - No runtime errors of “access to undefined variable”
  - Can check types of variables

Variable addresses for static scoping: first attempt

```
int x = 42;

int f() { return x; }
int g() { int x = 1; return f(); }
int main() { return g(); }
```

identifier	address
x (global)	0x42
x (inside g)	0x73

Variable addresses for static scoping: first attempt

```
int a [11] ;

void quicksort(int m, int n) {
  int i;
  if (n > m) {
    i = partition(m, n);
    quicksort (m, i-1) ;
    quicksort (i+1, n) ;
  }

main() {
…
 quicksort (1, 9) ;
}
```

what is the address of the variable “i” in the procedure quicksort?

Compile-Time Information on Variables

- Name
- Type
- Scope
  - when is it recognized
- Duration
  - Until when does its value exist
- Size
  - How many bytes are required at runtime
- Address
  - Fixed
  - Relative
  - Dynamic

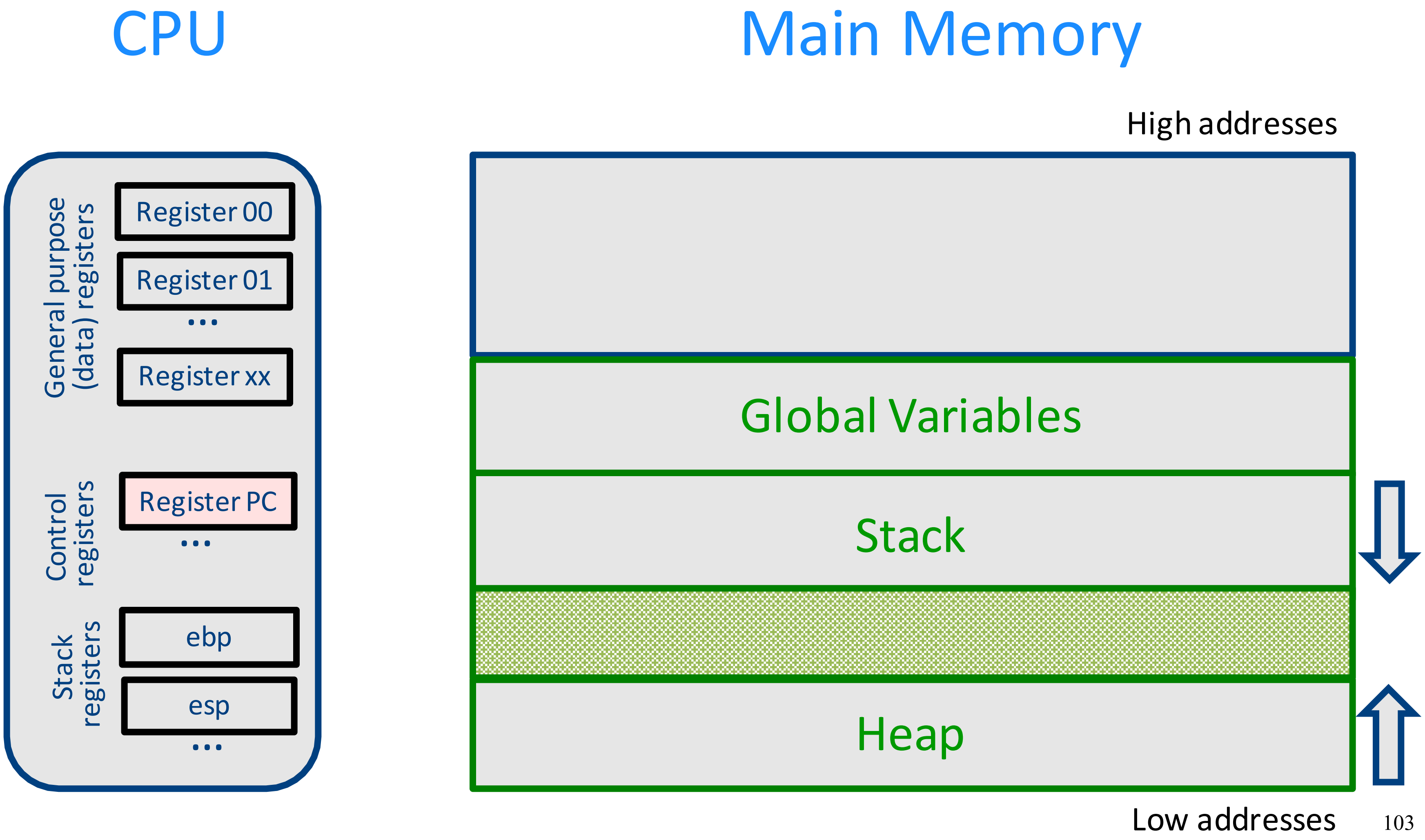
Activation Record (Stack Frames)

- separate space for each procedure invocation

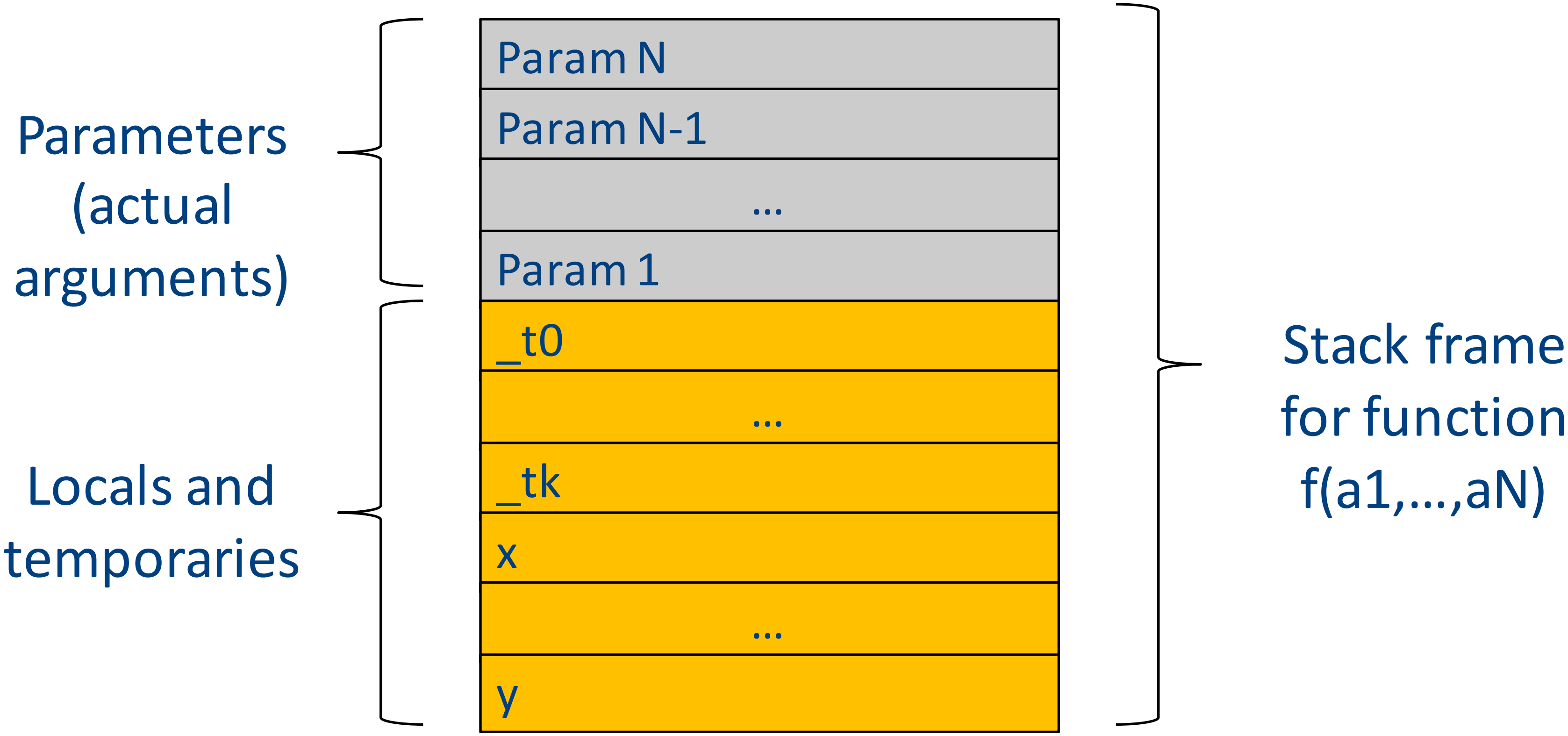
- **managed at runtime**
  - **code for managing it generated by the compiler**

- desired properties
  - efficient allocation and deallocation
    - procedures are called frequently
  - variable size
    - different procedures may require different memory sizes

Semi-Abstract Register Machine



A Logical Stack Frame (Simplified)



Parameters (actual arguments)

Param N

Param N-1

…

Param 1

_t0

…

_tk

x

…

y

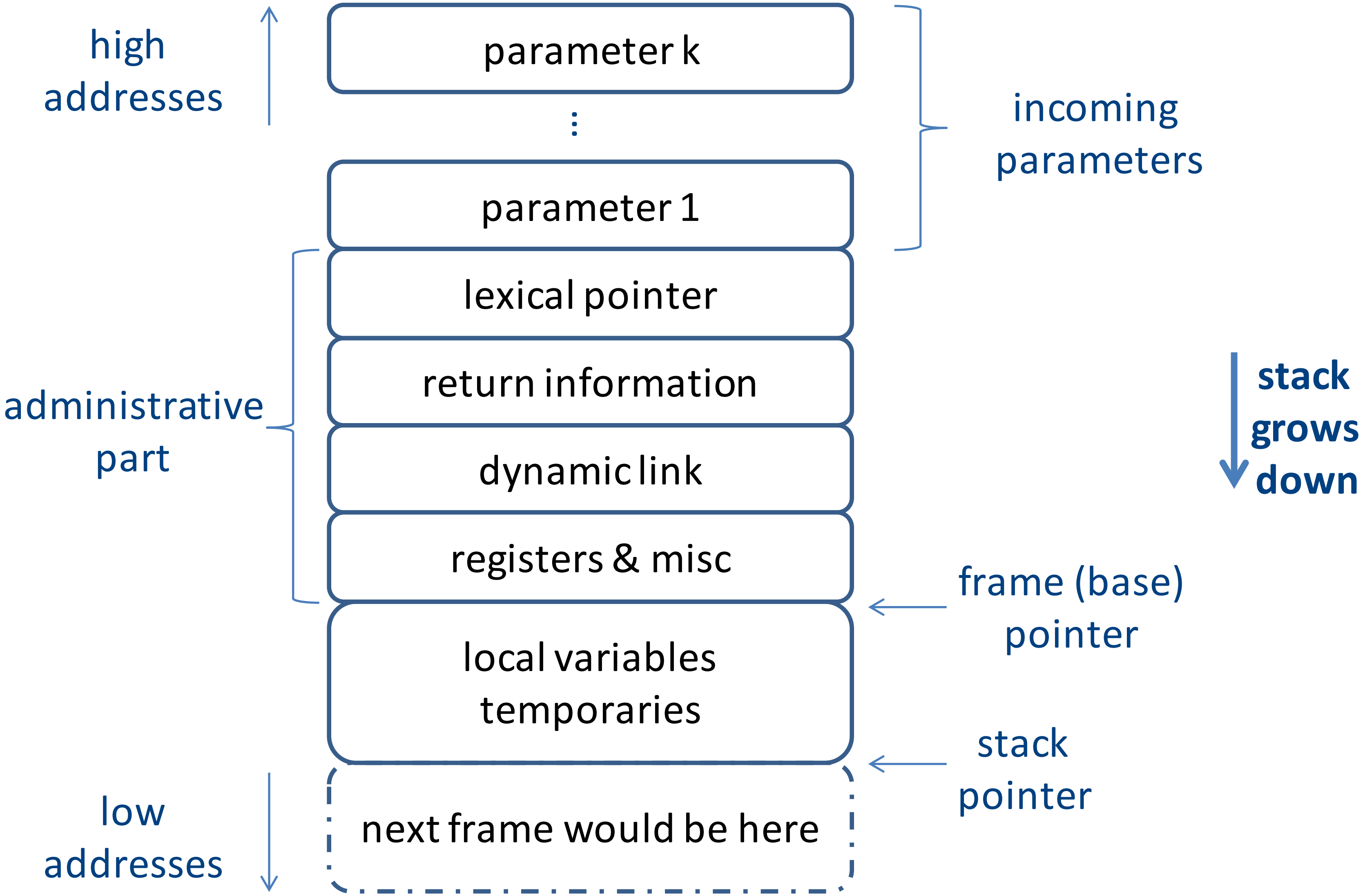
Locals and temporaries

Stack frame for function f(a1,…,aN)

Runtime Stack

- Stack of activation records
- Call = push new activation record
- Return = pop activation record
- Only one “active” activation record – top of stack
- How do we handle recursion?

Activation Record (frame)



high addresses

parameter k

⋮

parameter 1

incoming parameters

administrative part

lexical pointer

return information

dynamic link

registers & misc

stack grows down

frame (base) pointer

local variables temporaries

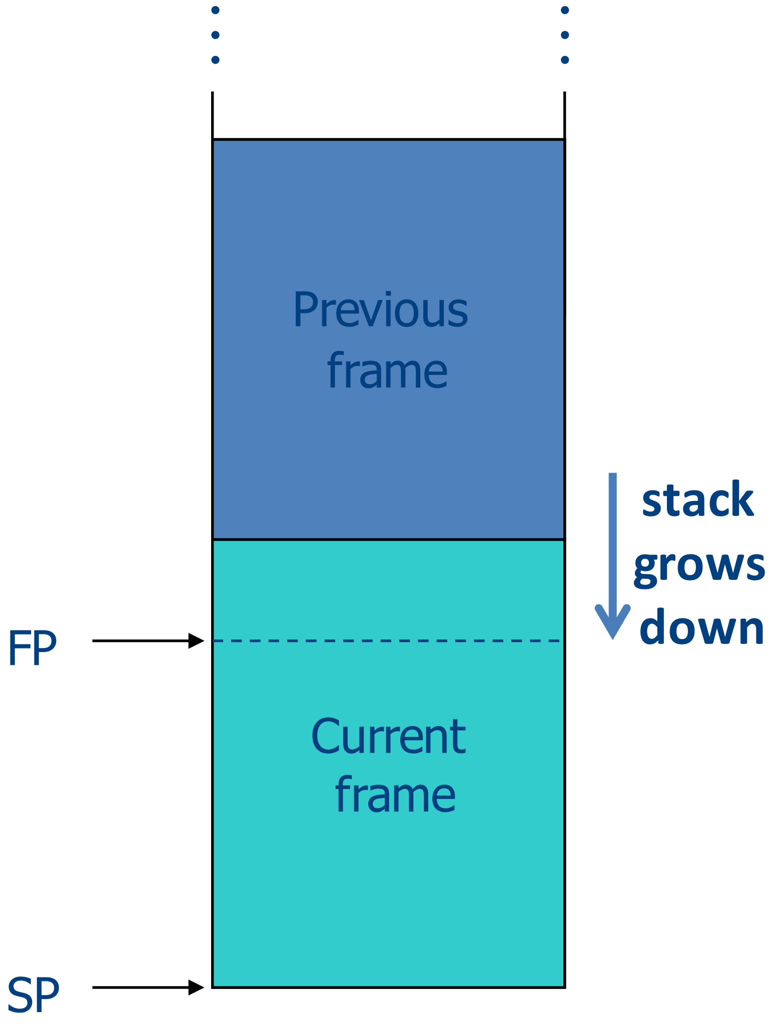
stack pointer

low addresses

next frame would be here

Runtime Stack

- SP – stack pointer
  – top of current frame
- FP – frame pointer
  – base of current frame
  - Sometimes called BP (base pointer)
  - Usually points to a “fixed” offset from the “start” of the frame



Code Blocks

- Programming language provide code blocks

```
void foo()
{
 int x = 8 ; y=9;//1
   { int x = y * y ;//2 }
   { int x = y * 7 ;//3}
       x = y + 1;
 }
```

adminstrative
x1
y1
x2
x3
…

L-Values of Local Variables

- The offset in the stack is known at compile time
- L-val(x) = FP+offset(x)
- x = 5 ⇒ Load_Constant 5, R3

  Store R3, offset(x)(FP)

Pentium Runtime Stack

Register	Usage
ESP	Stack pointer
EBP	Base pointer

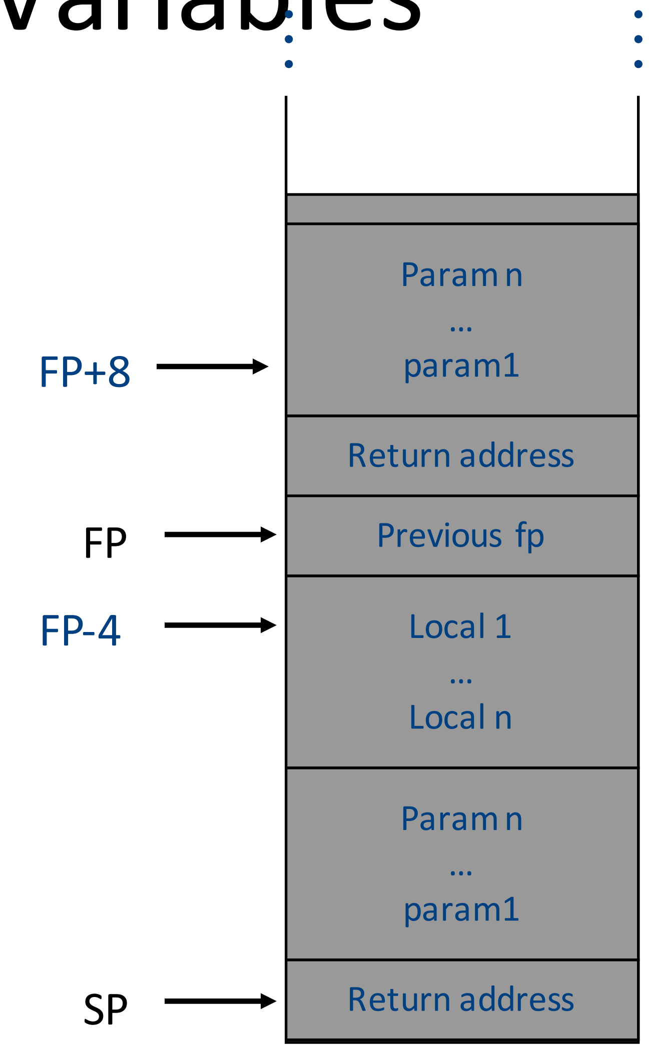
Pentium stack registers

Instruction	Usage
push, pusha,…	push on runtime stack
pop,popa,…	Base pointer
call	transfer control to called routine
return	transfer control back to caller

Pentium stack and call/ret instructions

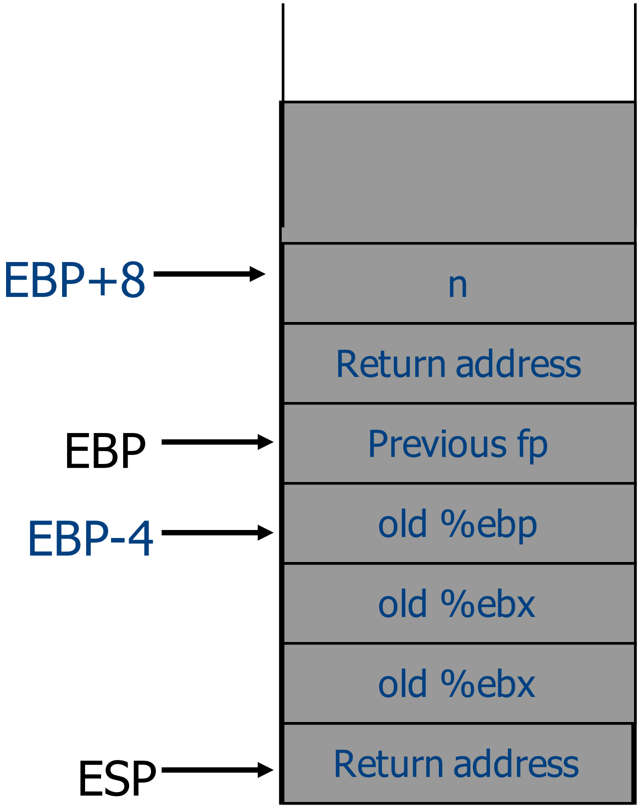
Accessing Stack Variables

- Use offset from FP (%ebp)
  - Remember: stack grows downwards
- Above FP = parameters
- Below FP = locals
- Examples
  - %ebp + 4 = return address
  - %ebp + 8 = first parameter
  - %ebp – 4 = first local



Factorial – `fact(int n)`

```
fact:
pushl %ebp              # save ebp
movl %esp,%ebp          # ebp=esp
pushl %ebx              # save ebx
movl 8(%ebp),%ebx       # ebx = n
cmpl $1,%ebx            # n = 1 ?
jle .lresult            # then done
leal -1(%ebx),%eax      # eax = n-1
pushl %eax              #
call fact               # fact(n-1)
imull %ebx,%eax         # eax=retv*n
jmp .lreturn            #
.lresult:
movl $1,%eax            # retv
.lreturn:
movl -4(%ebp),%ebx      # restore ebx
movl %ebp,%esp          # restore esp
popl %ebp               # restore ebp
```



(stack in intermediate point)

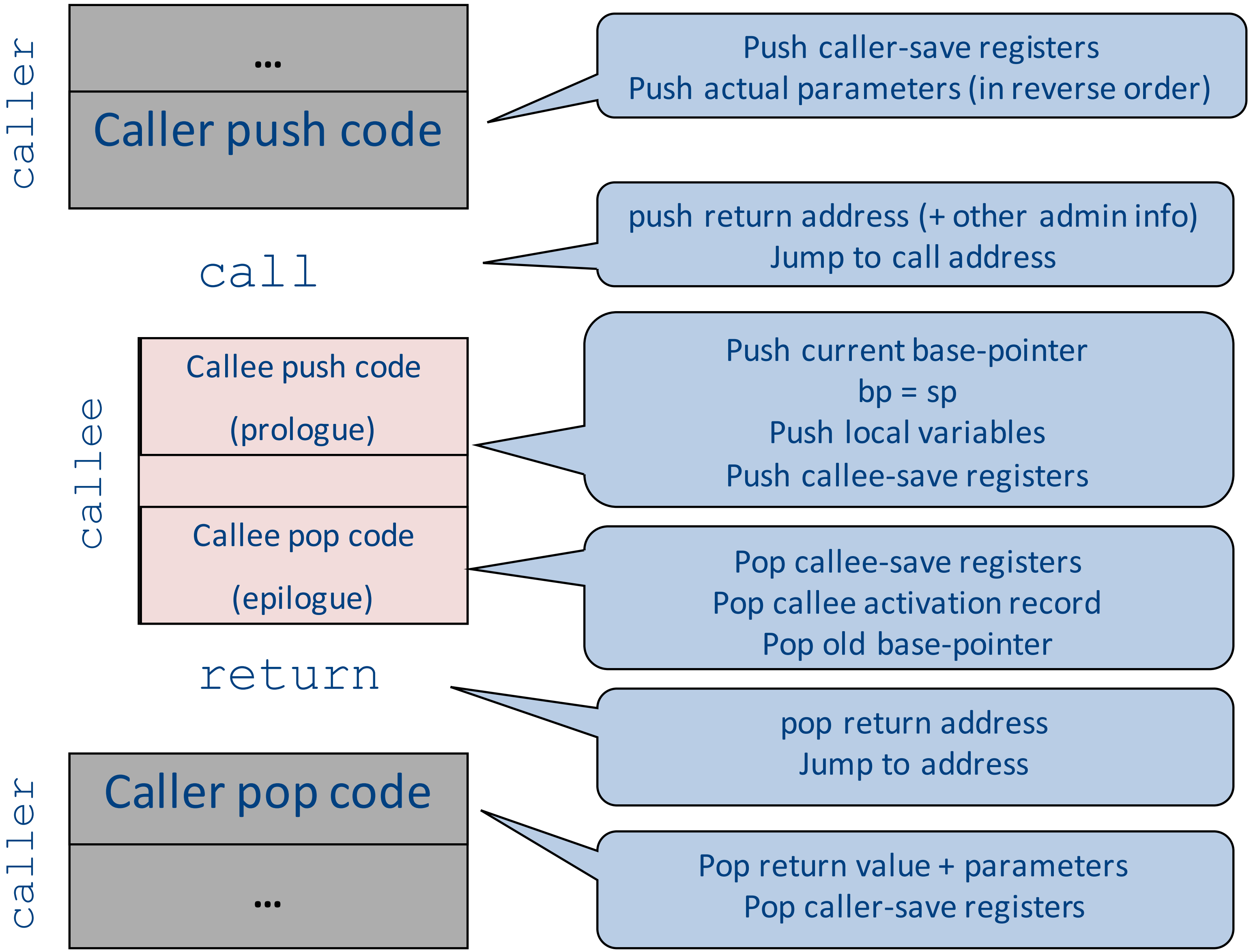
(disclaimer: real compiler can do better than that)

Call Sequences

- The **processor** **does not save** the content of **registers** on procedure calls

- So who will?
  - Caller saves and restores registers
  - Callee saves and restores registers
  - But can also have both save/restore some registers

Call Sequences



caller

…

Caller push code

Push caller-save registers
Push actual parameters (in reverse order)

call

push return address (+ other admin info)
Jump to call address

callee

Callee push code
(prologue)

Push current base-pointer
bp = sp
Push local variables
Push callee-save registers

Callee pop code
(epilogue)

Pop callee-save registers
Pop callee activation record
Pop old base-pointer

return

pop return address
Jump to address

caller

Caller pop code

…

Pop return value + parameters
Pop caller-save registers

“To Callee-save or to Caller-save?”

- Callee-saved registers need only be saved when callee modifies their value
- Some heuristics and conventions are followed

Caller-Save and Callee-Save Registers

- Callee-Save Registers
  - Saved by the callee before modification
  - Values are automatically preserved across calls
- Caller-Save Registers
  - Saved (if needed) by the caller before calls
  - Values are not automatically preserved across calls
- Usually the architecture defines caller-save and callee-save registers

- Separate compilation
- Interoperability between code produced by different compilers/languages
- But compiler writers decide when to use caller/callee registers

Callee-Save Registers

- Saved by the callee before modification
- Usually at procedure prolog
- Restored at procedure epilog
- Hardware support may be available
- Values are automatically preserved across calls

```
int foo(int a)    {
        int b=a+1;
        f1();
        g1(b);
        return(b+2);
}
```

```
.global _foo
     Add_Constant  -K, SP //allocate space for foo
     Store_Local   R5, -14(FP) // save R5
     Load_Reg   R5, R0; Add_Constant  R5, 1
     JSR  f1 ; JSR g1;
     Add_Constant  R5, 2; Load_Reg R5, R0
    Load_Local  -14(FP), R5 // restore R5
    Add_Constant  K, SP; RTS // deallocate
```

Caller-Save Registers

- Saved by the caller before calls when needed
- Values are not automatically preserved across calls

```
void bar (int y) {
        int x=y+1;
        f2(x);
        g2(2);
        g2(8);
}
```

```
.global _bar
            Add_Constant -K, SP //allocate space for bar
            Add_Constant R0, 1
            JSR f2
            Load_Constant  2, R0  ;       JSR g2;
            Load_Constant 8, R0 ;         JSR g2
            Add_Constant K, SP // deallocate space for bar
             RTS
```

Parameter Passing

- 1960s
  - In memory
    - No recursion is allowed
- 1970s
  - In stack
- 1980s
  - In registers
  - First k parameters are passed in registers (k=4 or k=6)
  - Where is time saved?

- Most procedures are leaf procedures
- Interprocedural register allocation
- Many of the registers may be dead before another invocation
- Register windows are allocated in some architectures per call (e.g., sun Sparc)

Activation Records & Language Design

Compile-Time Information on Variables

- Name, type, size
- Address kind
  - Fixed (global)
  - Relative (local)
  - Dynamic (heap)
- Scope
  - when is it recognized
- Duration
  - Until when does its value exist

Scoping

```
int x = 42;

int f() { return x; }
int g() { int x = 1; return f(); }
int main() { return g(); }
```

- What value is returned from main?
- Static scoping?
- Dynamic scoping?

Nested Procedures

- For example – Pascal
- Any routine can have sub-routines
- Any sub-routine can access anything that is defined in its containing scope or inside the sub-routine itself
  - “non-local” variables

Example: Nested Procedures

```
program p(){
  int x;
  procedure a(){
    int y;
    procedure b(){ … c() … };
    procedure c(){
      int z;
      procedure d(){
        y := x + z
      };
      … b() … d() …
    }
    … a() … c() …
  }
  a()
}
```

Possible call sequence:
p → a → a → c → b → c → d

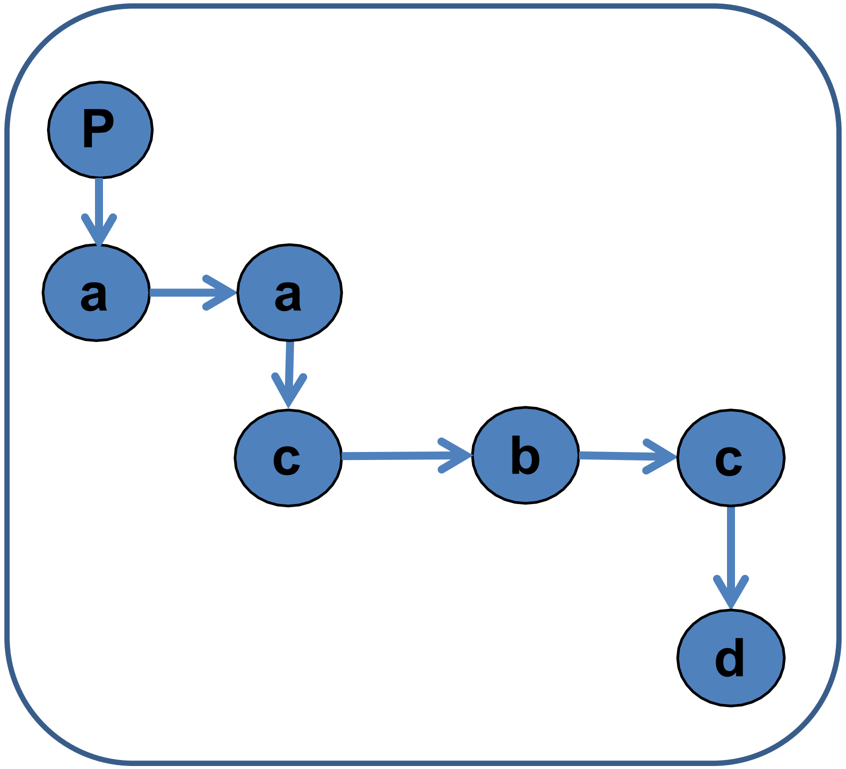
what are the addresses of variables “x,” “y” and “z” in procedure d?

Nested Procedures

- **can call a sibling, ancestor**
- when “c” uses (non-local) variables from “a”, which instance of “a” is it?

- how do you find the right activation record at runtime?

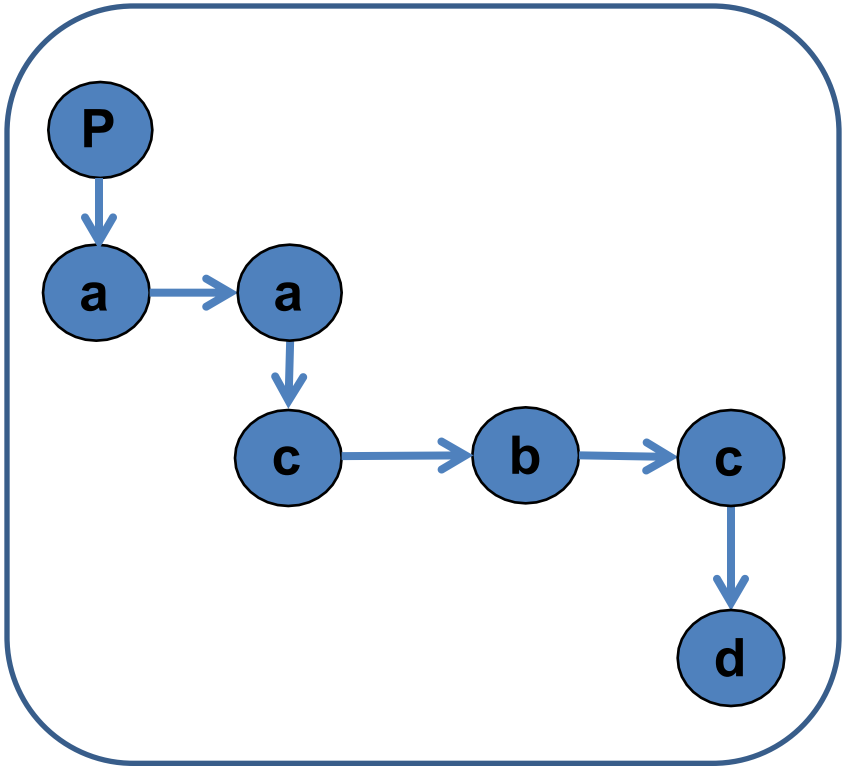
Possible call sequence:
p → a → a → c → b → c → d



Nested Procedures

- goal: **find the closest routine in the stack from a given nesting level**
- if we reached the same routine in a sequence of calls
  - routine of level k uses variables of the same nesting level, it uses its own variables
  - if it uses variables of nesting level j < k then it must be the last routine called at level j
- If a procedure is last at level j on the stack, then it must be ancestor of the current routine

Possible call sequence:
p → a → a → c → b → c → d



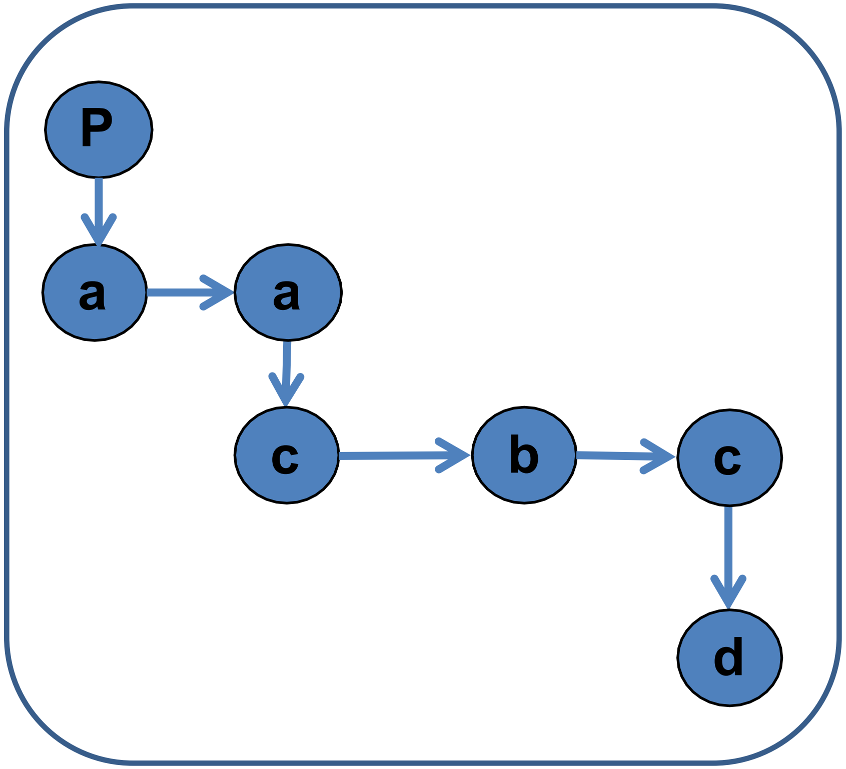
Nested Procedures

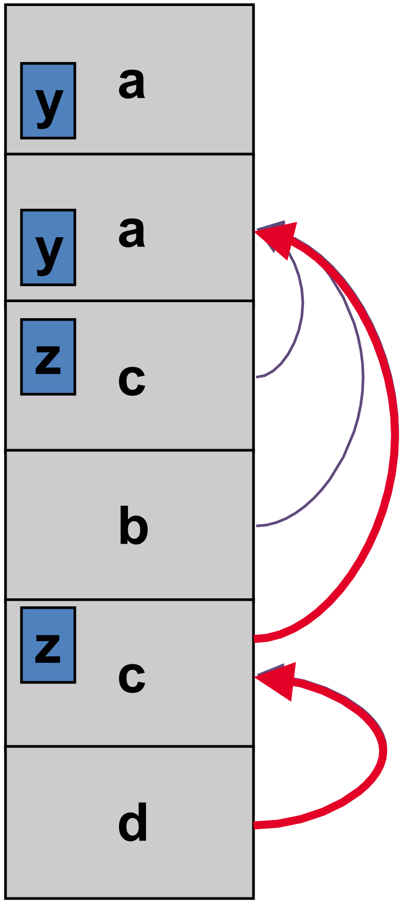
- problem: a routine may need to access variables of another routine that contains it statically
- solution: lexical pointer (a.k.a. access link) in the activation record
- lexical pointer points to the last activation record of the nesting level above it
  - in our example, lexical pointer of d points to activation records of c
- lexical pointers created at runtime
- number of links to be traversed is known at compile time

Lexical Pointers

```
program p(){
  int x;
  procedure a(){
    int y;
    procedure b(){ c() };
     procedure c(){
       int z;
       procedure d(){
         y := x + z
       };
       … b() … d() …
     }
    … a() … c() …
  }
  a()
}
```

Possible call sequence:
p → a → a → c → b → c → d

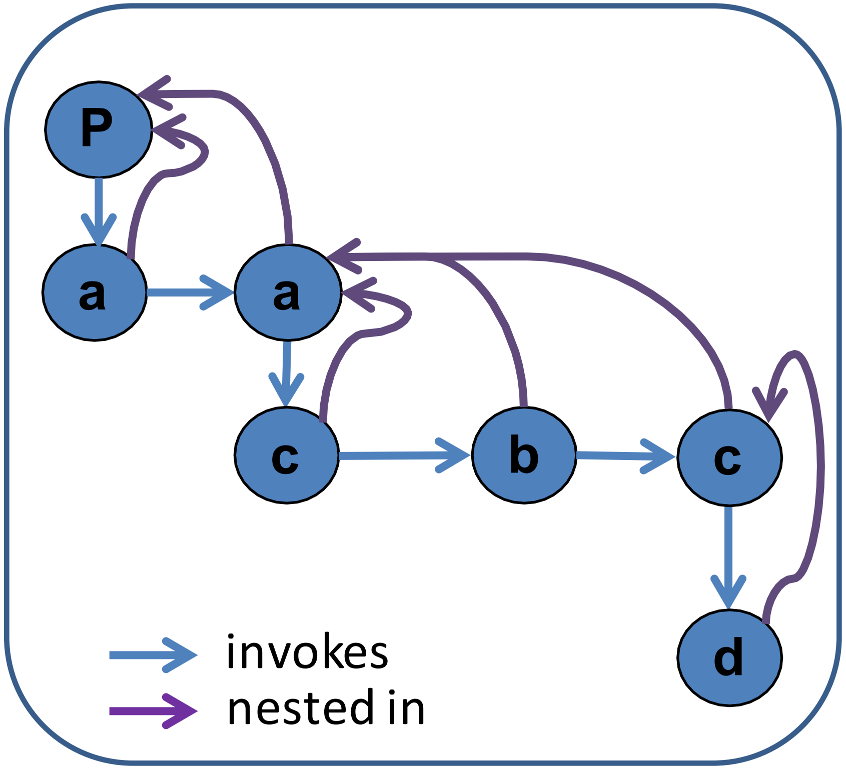


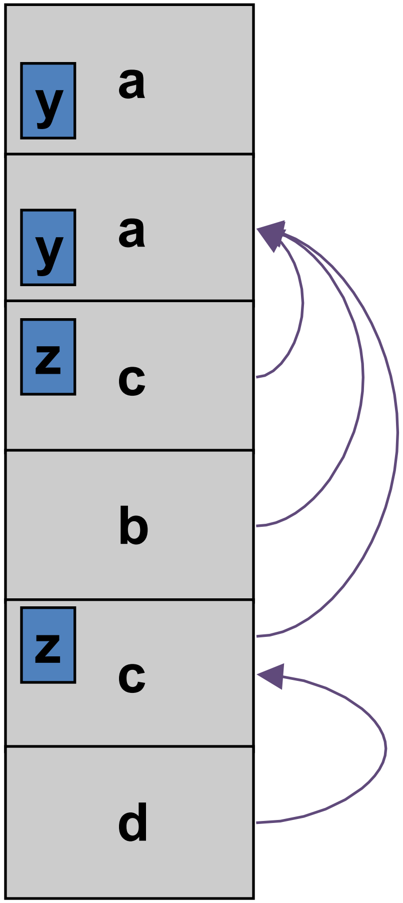


Lexical Pointers

```
program p(){
  int x;
  procedure a(){
    int y;
    procedure b(){ c() };
     procedure c(){
       int z;
       procedure d(){
         y := x + z
       };
       … b() … d() …
     }
    … a() … c() …
  }
  a()
}
```

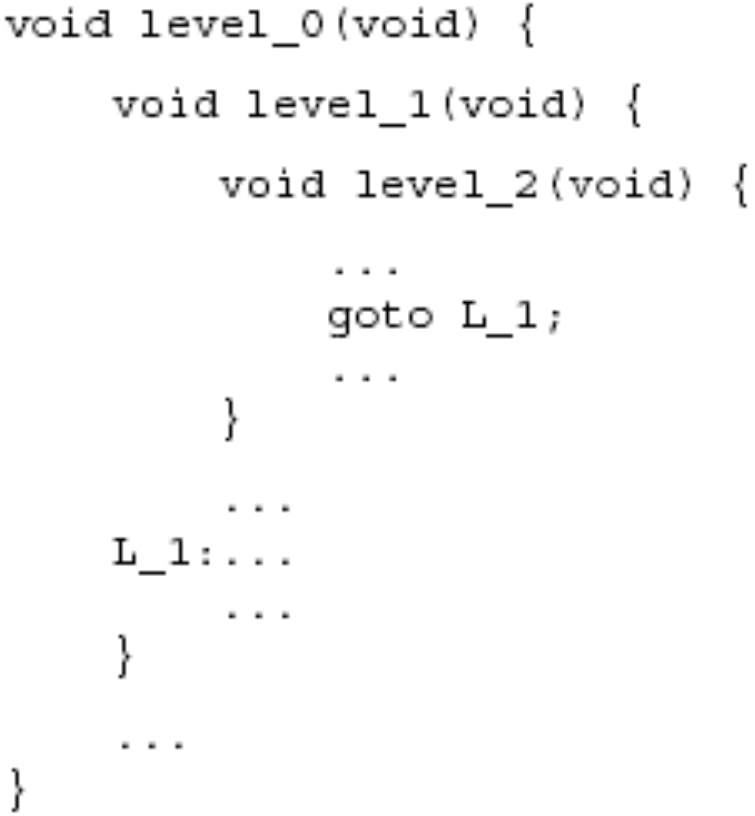
Possible call sequence:
p → a → a → c → b → c → d





Activation Records: Remarks

Non-Local goto in C syntax

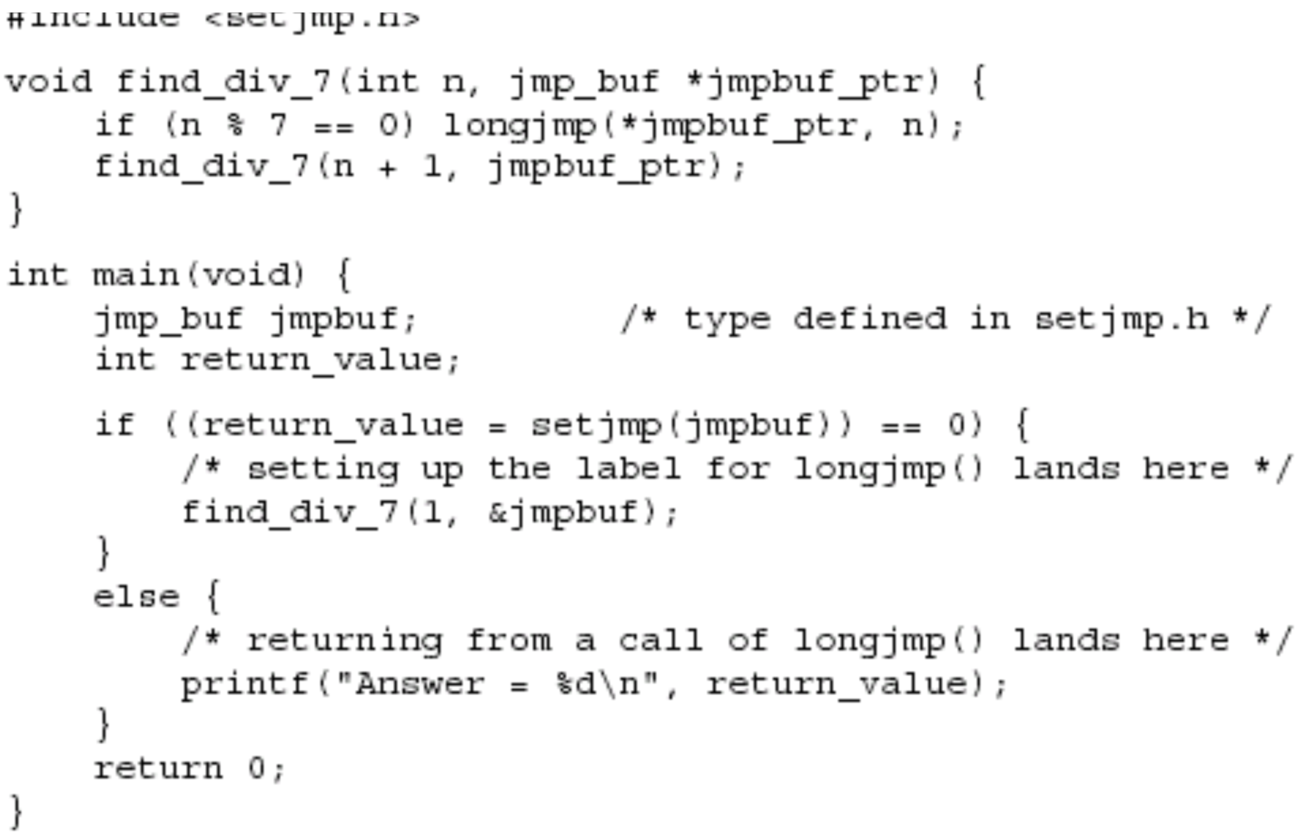


```
void level_0(void) {
    void level_1(void) {
        void level_2(void) {
            ...
            goto L_1;
            ...
        }
        ...
    L_1:...
        ...
    }
    ...
}
```

Non-local gotos in C

- setjmp remembers the current location and the stack frame
- longjmp jumps to the current location (popping many activation records)

Non-Local Transfer of Control in C



```
#include <setjmp.h>

void find_div_7(int n, jmp_buf *jmpbuf_ptr) {
    if (n % 7 == 0) longjmp(*jmpbuf_ptr, n);
    find_div_7(n + 1, jmpbuf_ptr);
}

int main(void) {
    jmp_buf jmpbuf;         /* type defined in setjmp.h */
    int return_value;

    if ((return_value = setjmp(jmpbuf)) == 0) {
        /* setting up the label for longjmp() lands here */
        find_div_7(1, &jmpbuf);
    }
    else {
        /* returning from a call of longjmp() lands here */
        printf("Answer = %d\n", return_value);
    }
    return 0;
}
```

Stack Frames

- Allocate a separate space for every procedure incarnation
- Relative addresses
- Provide a simple mean to achieve modularity
- Supports separate code generation of procedures
- Naturally supports recursion
- Efficient memory allocation policy
  - Low overhead
  - Hardware support may be available
- LIFO policy
- Not a pure stack
  - Non local references
  - Updated using arithmetic

The Frame Pointer

- The caller
  - the calling routine
- The callee
  - the called routine
- caller responsibilities:
  - Calculate arguments and save in the stack
  - Store lexical pointer
- call instruction:

  M[--SP] := RA
  PC := callee
- callee responsibilities:
  - FP := SP
  - SP := SP - frame-size
- Why use both SP and FP?

Variable Length Frame Size

- C allows allocating objects of unbounded size in the stack

```
 void p() {
    int i;
    char *p;
    scanf(“%d”, &i);
    p = (char *) alloca(i*sizeof(int));
  }
```

- Some versions of Pascal allows conformant array value parameters

Limitations

- The compiler may be forced to store a value on a stack instead of registers
- The stack may not suffice to handle some language features

Frame-Resident Variables

- A variable x cannot be stored in register when:
  - x is passed by reference
  - Address of x is taken (&x)
  - is addressed via pointer arithmetic on the stack-frame (C varags)
  - x is accessed from a nested procedure
  - The value is too big to fit into a single register
  - The variable is an array
  - The register of x is needed for other purposes
  - Too many local variables
- An escape variable:
  - Passed by reference
  - Address is taken
  - Addressed via pointer arithmetic on the stack-frame
  - Accessed from a nested procedure

The Frames in Different Architectures

g(x, y, z) where x escapes

	Pentium	MIPS	Sparc
x	InFrame(8)	InFrame(0)	InFrame(68)
y	InFrame(12)	InReg(X_{157})	InReg(X_{157})
z	InFrame(16)	InReg(X_{158})	InReg(X_{158})

View Change	M[sp+0]←fp
	fp ←sp
	sp ←sp-K
		sp ←sp-K
		M[sp+K+0] ←r_2
		X_{157} ←r4
		X_{158} ←r5
			save %sp, -K, %sp
			M[fp+68]←i_0
			X_{157}←i_1
			X_{158}←i_2

Limitations of Stack Frames

- A local variable of P cannot be stored in the activation record of P if its duration exceeds the duration of P
- Example 1: Static variables in C
  (own variables in Algol)

```
void p(int x)
{
   static int y = 6 ;
   y += x;
 }
```

- Example 2: Features of the C language

```
int * f()
{ int x ;
   return &x ;
}
```

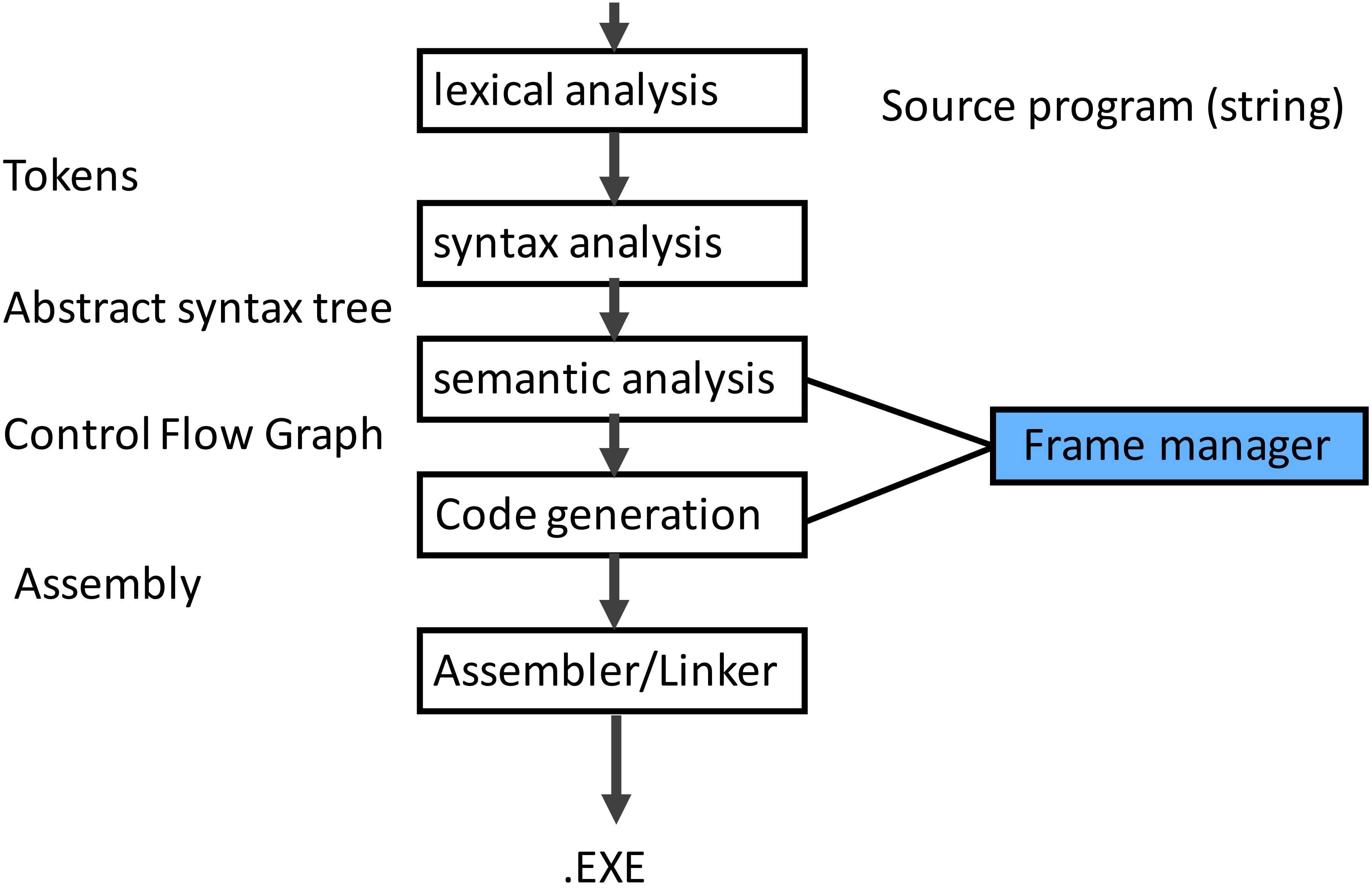
- Example 3: Dynamic allocation

```
int * f()  { return (int *)
malloc(sizeof(int)); }
```

Compiler Implementation

- Hide machine dependent parts
- Hide language dependent part
- Use special modules

Basic Compiler Phases



Source program (string)

lexical analysis

Tokens

syntax analysis

Abstract syntax tree

semantic analysis

Control Flow Graph

Code generation

Frame manager

Assembly

Assembler/Linker

.EXE

Hidden in the frame ADT

- Word size
- The location of the formals
- Frame resident variables
- Machine instructions to implement “shift-of-view” (prologue/epilogue)
- The number of locals “allocated” so far
- The label in which the machine code starts

Activation Records: Summary

- compile time memory management for procedure data
- works well for data with well-scoped lifetime
  - deallocation when procedure returns