Compilation

0368-3133 (Semester A, 2013/14)

Lecture 8: Activation Records + Register Allocation

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Slides credit: Roman Manevich, Mooly Sagiv and Eran Yahav

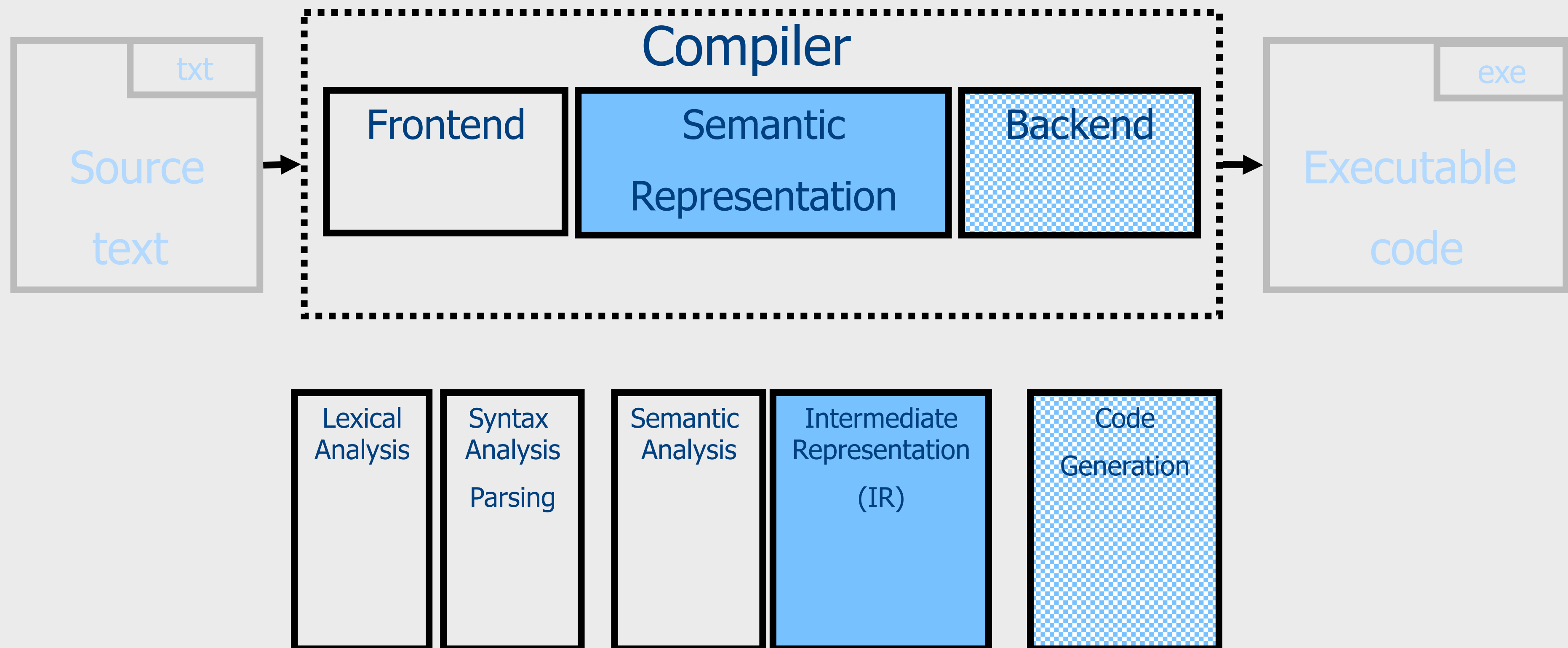
What is a Compiler?

“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

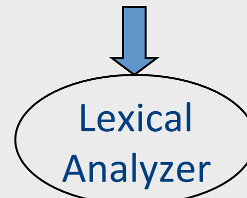
Conceptual Structure of a Compiler



From scanning to parsing

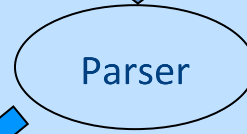
program text

((23 + 7) * x)



token stream

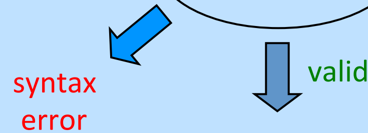
(	(	23	+	7	)	*	x	)
LP	LP	Num	OP	Num	RP	OP	Id	RP



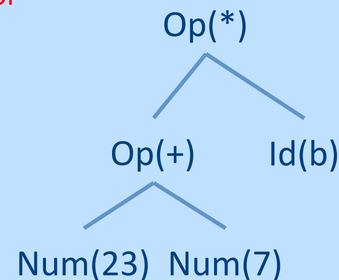
Grammar:

E → ... | Id

Id → 'a' | ... | 'z'



valid

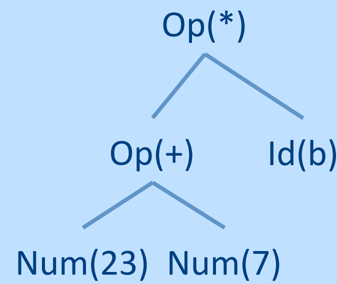


Abstract Syntax Tree

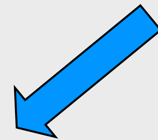
Context Analysis

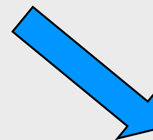
Type rules

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



Abstract Syntax Tree



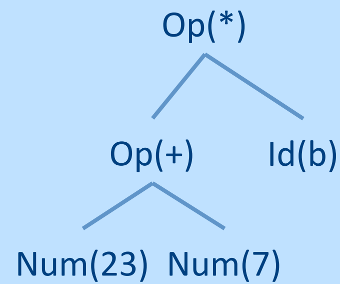


Semantic Error

Valid + Symbol Table

Code Generation

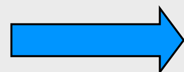
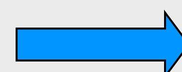
...



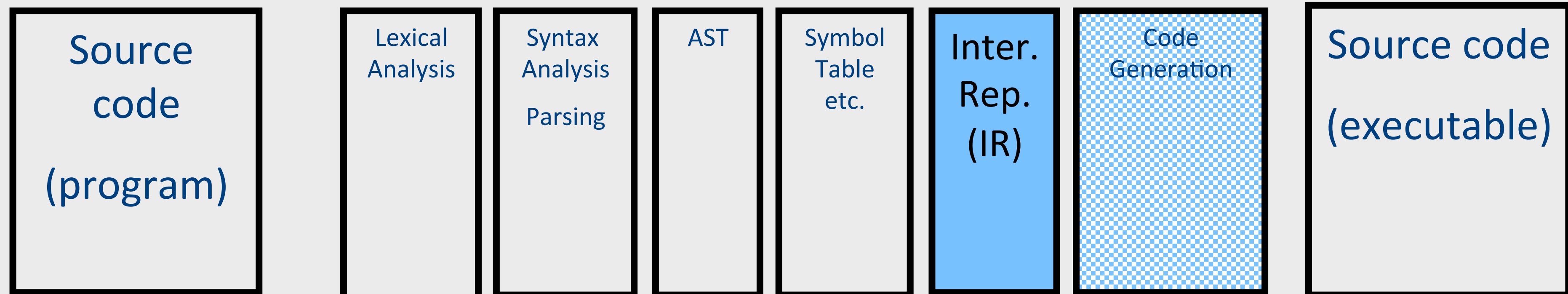
Valid Abstract Syntax Tree
Symbol Table

Verification (possible runtime)
Errors/Warnings

Intermediate Representation (IR)

input  Executable Code  output

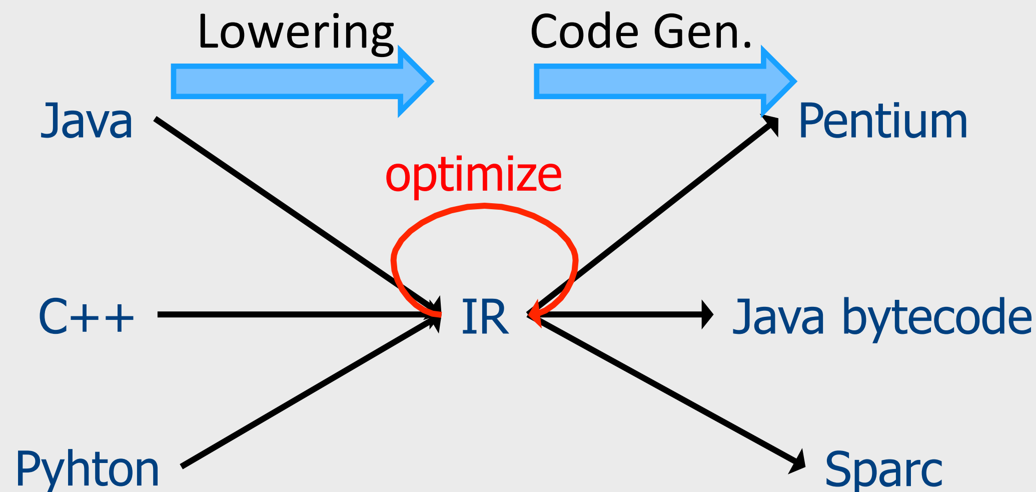
Code Generation: IR



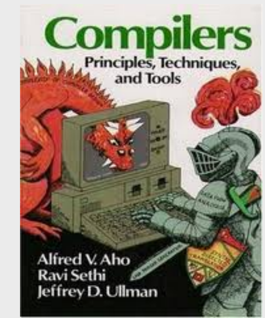
- Translating from abstract syntax (AST) to intermediate representation (IR)
  - **T**hree-**A**ddress **C**ode
    - Primitive statements, control flow, procedure calls

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 node types (instructions)



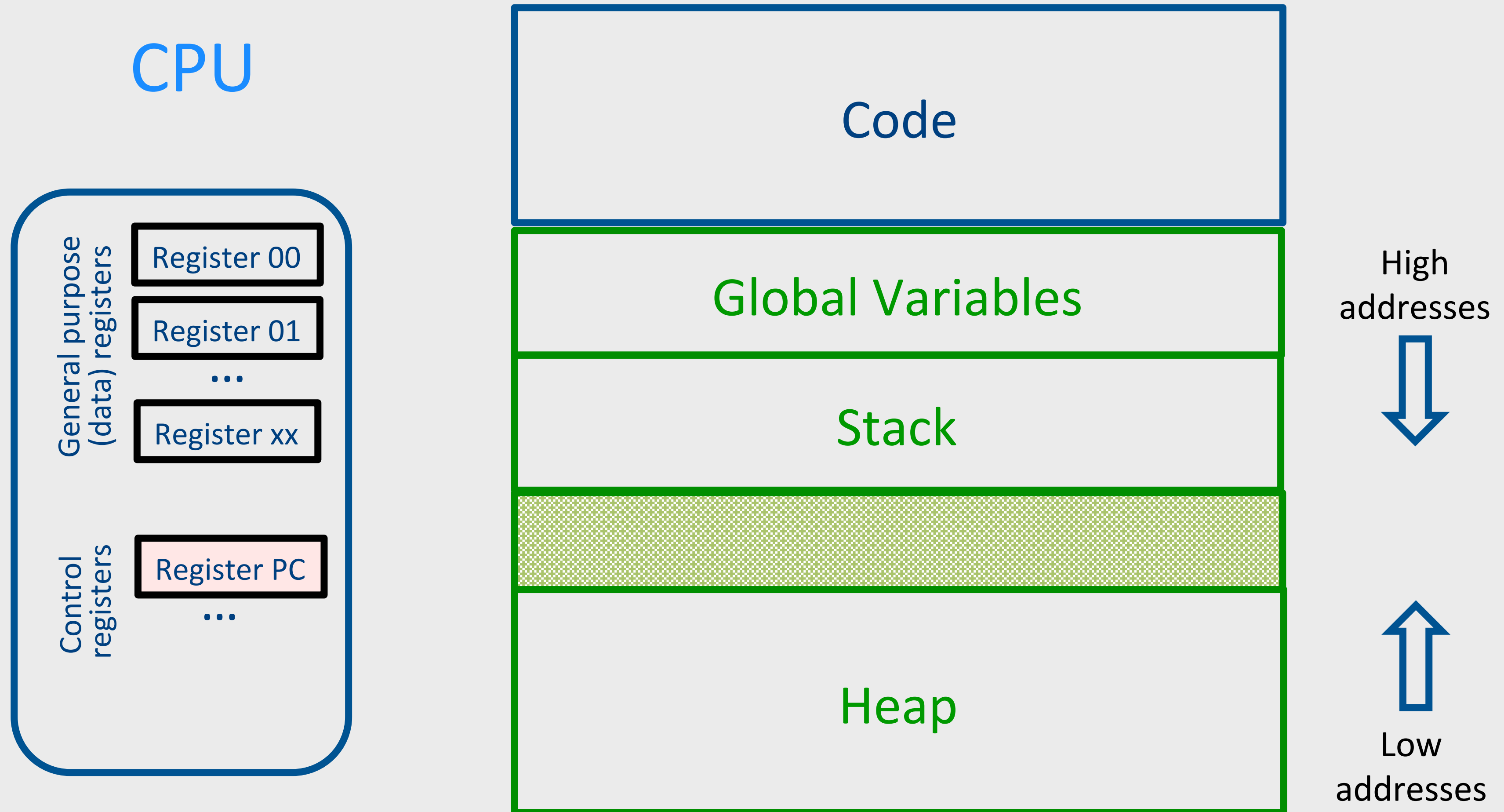
Three-Address Code IR



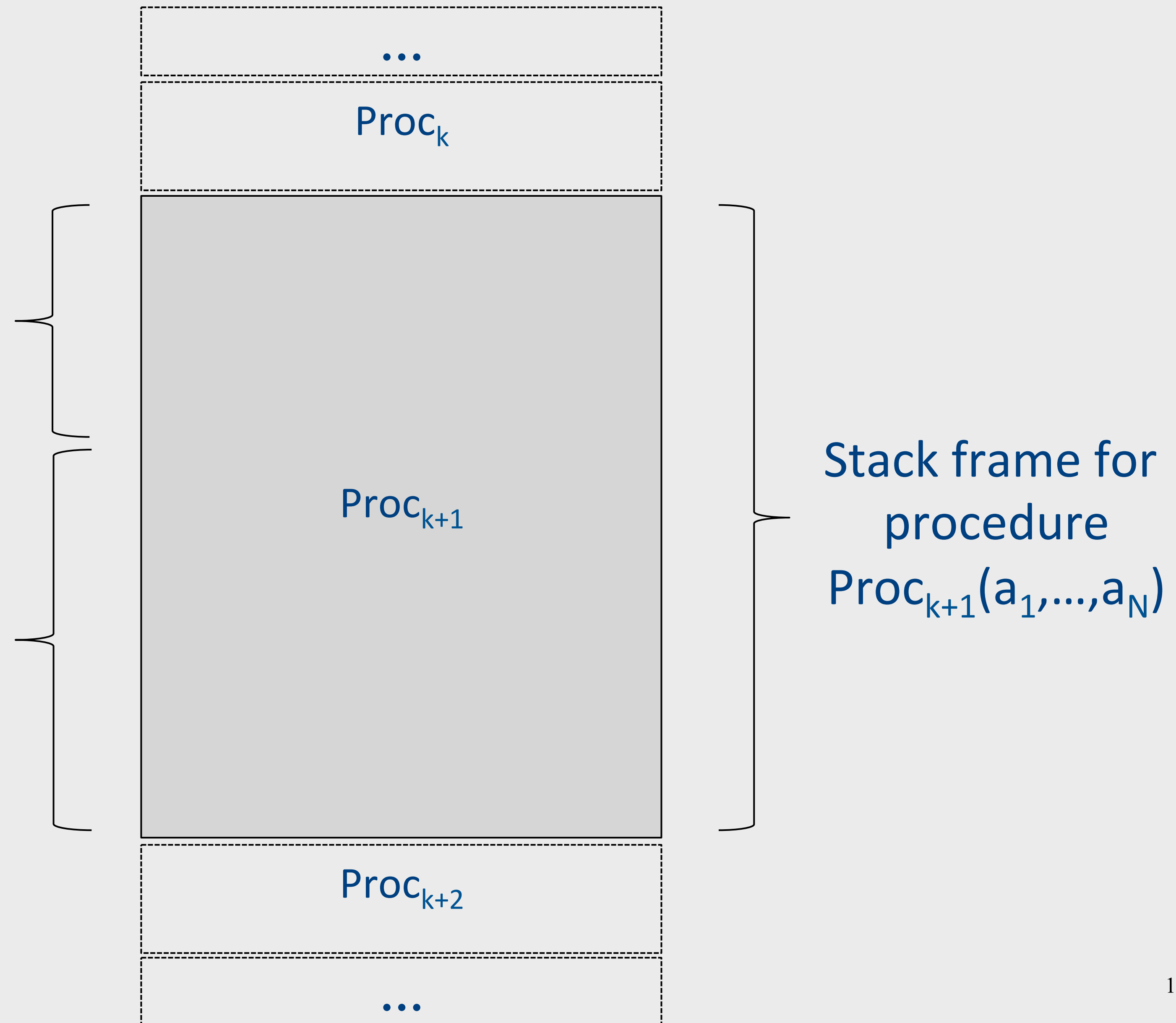
Chapter 8

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

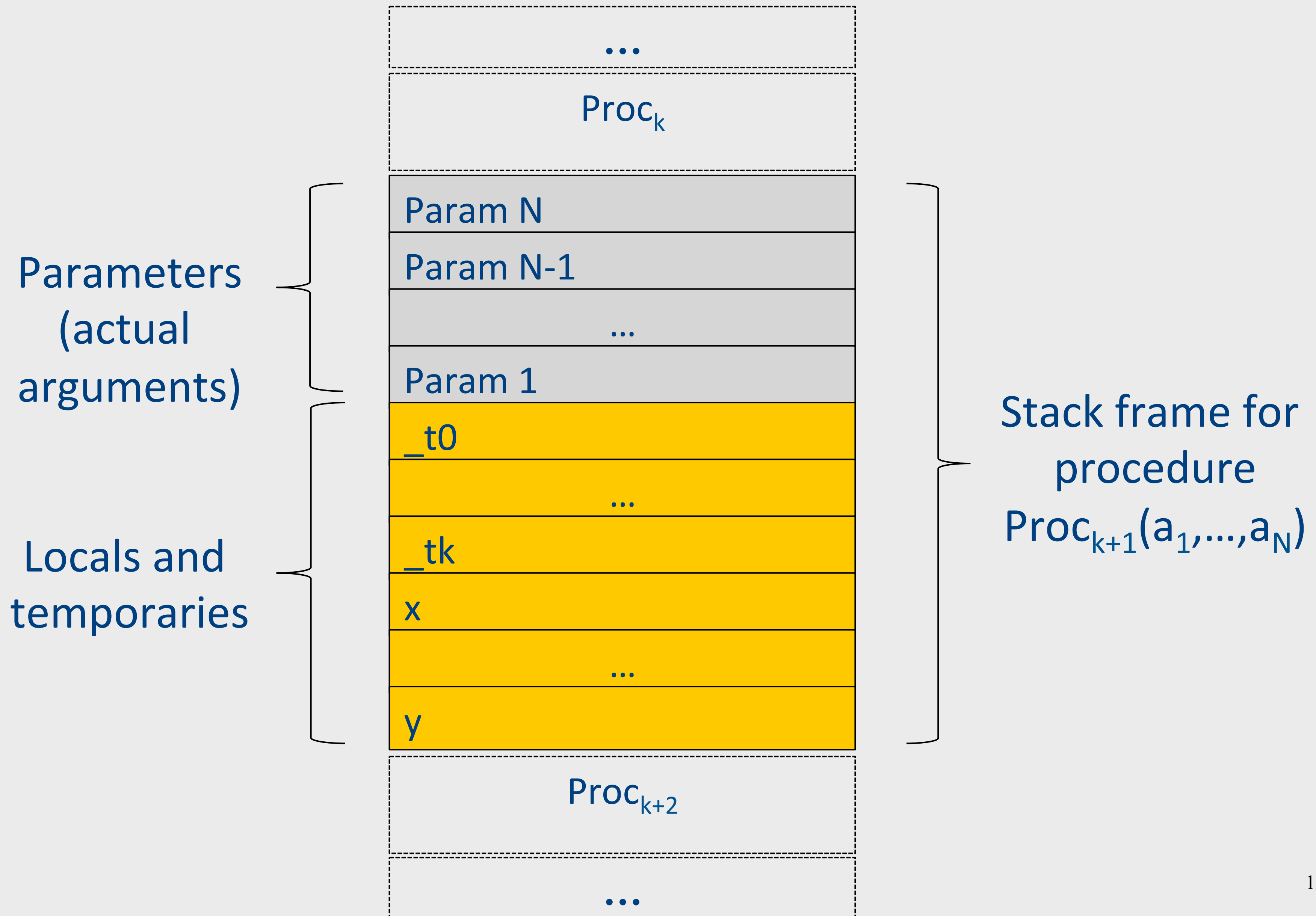
Abstract Register Machine



Abstract Activation Record Stack



Abstract Stack Frame



TAC generation for expressions

- **cgen**(*atomic_expr)* directly generates TAC for atomic expressions
  - Constants, identifiers,…
- **Cgen**(*compund_expr)* recursively generates TAC for compound expressions
  - binary operators, procedure calls, …
  - use temporary variables (**registers**) to store values of intermediate expressions

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*

}

Naïve **cgen** for expressions

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

```
    Let A = cgen(e1)
    c = c + 1
    Let B = cgen(e2)
    c = c + 1
    Emit( _tc = A op B; )
    Return _tc
}
```

TAC Generation for Control Flow Statements

- 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 1, 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;
```

cgen for `if-then-else`

cgen(if (e) s_1 else s_2)

```
Let _t = cgen(e)
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: )
```

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

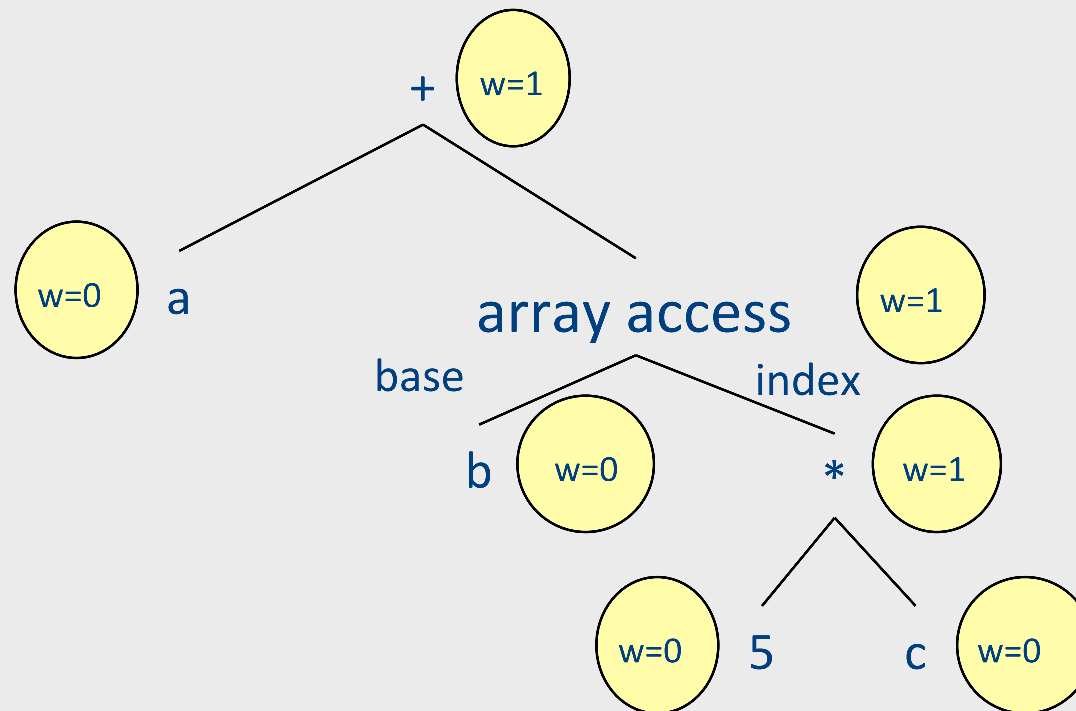
Weighted register allocation

- 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])

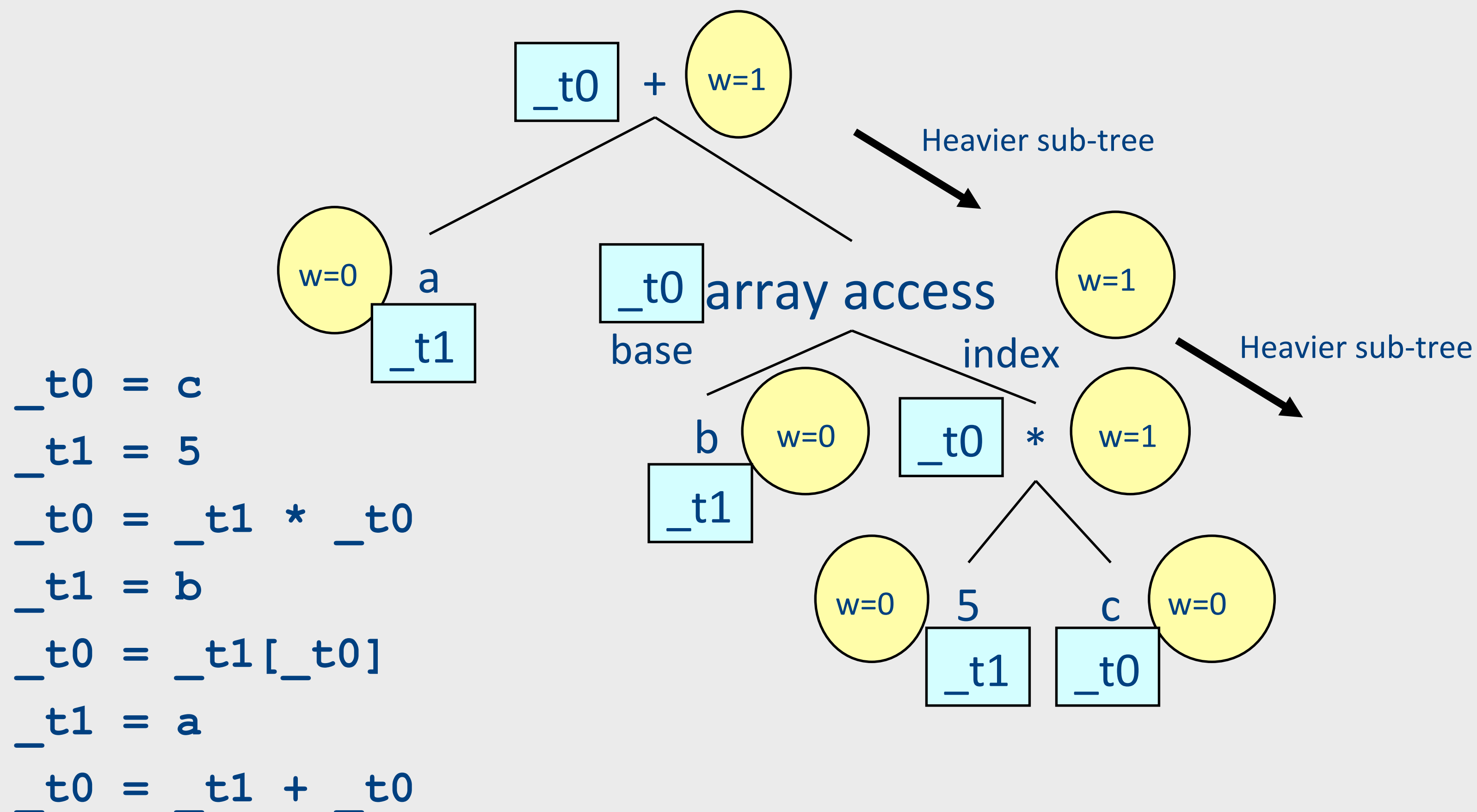
Phase 1: - check absence of side-effects in expression tree
- assign weight to each AST node



Weighted reg. alloc. example

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

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



TAC Generation for 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      ; value stored 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
```

TAC Generation for Control Flow Statements

- 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;
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```
IfZ t Goto L;
```

- Similarly : test condition variable t;
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```
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```

Control-flow example – conditions

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

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

cgen for `if-then-else`

cgen(if (e) s_1 else s_2)

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Let _t = cgen(e)
Let L_false be a new label
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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: )
```

Control-flow example – loops

```
int x;
int y;

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

y = x;
```

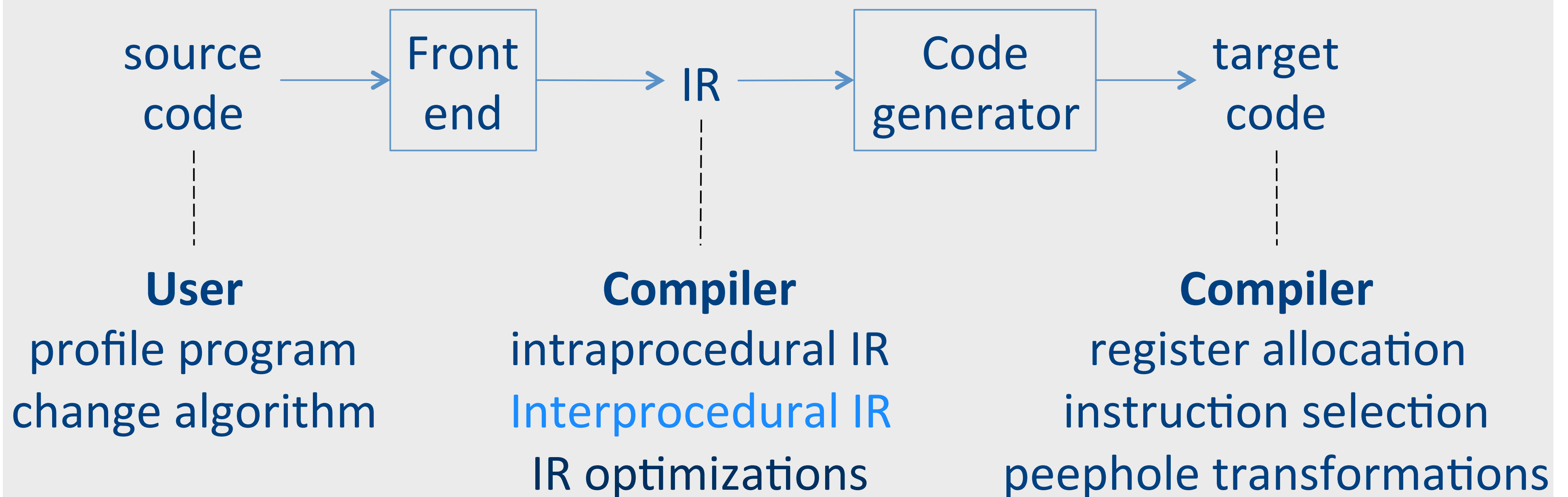
```
_L0:
      _t0 = x < y;
      IfZ _t0 Goto _L1;
      x = x * 2;
      Goto _L0;
_L1:
      y = x;
```

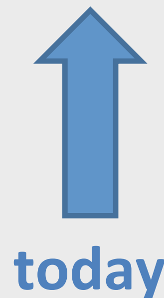
cgen for `while` loops

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 L_after; )
cgen(stmt)
Emit( Goto L_before; )
Emit( L_after: )
```

Optimization points





today

Interprocedural IR

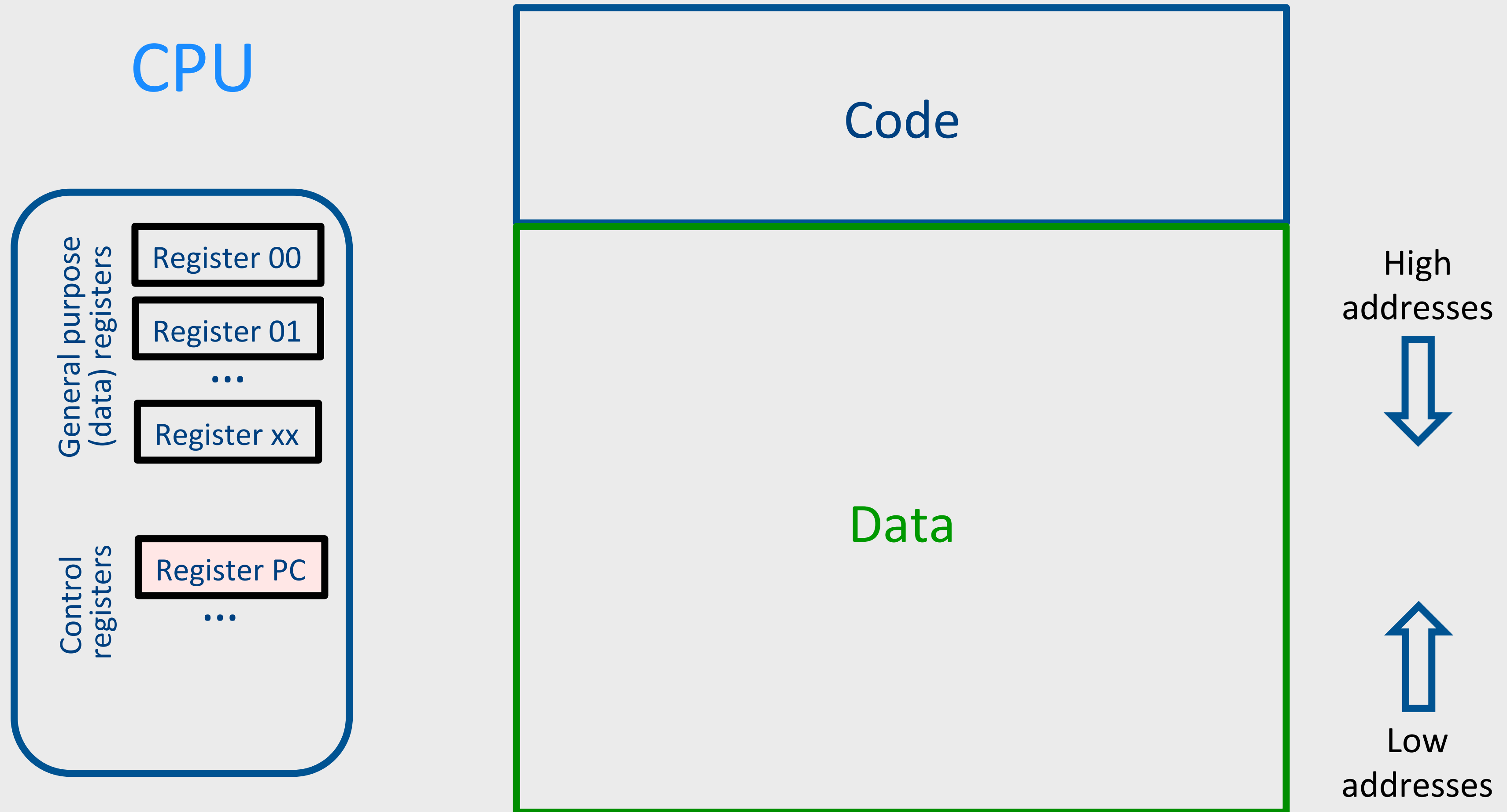
- Compile time generation of code for procedure invocations

- Activation Records (aka Stack Frames)

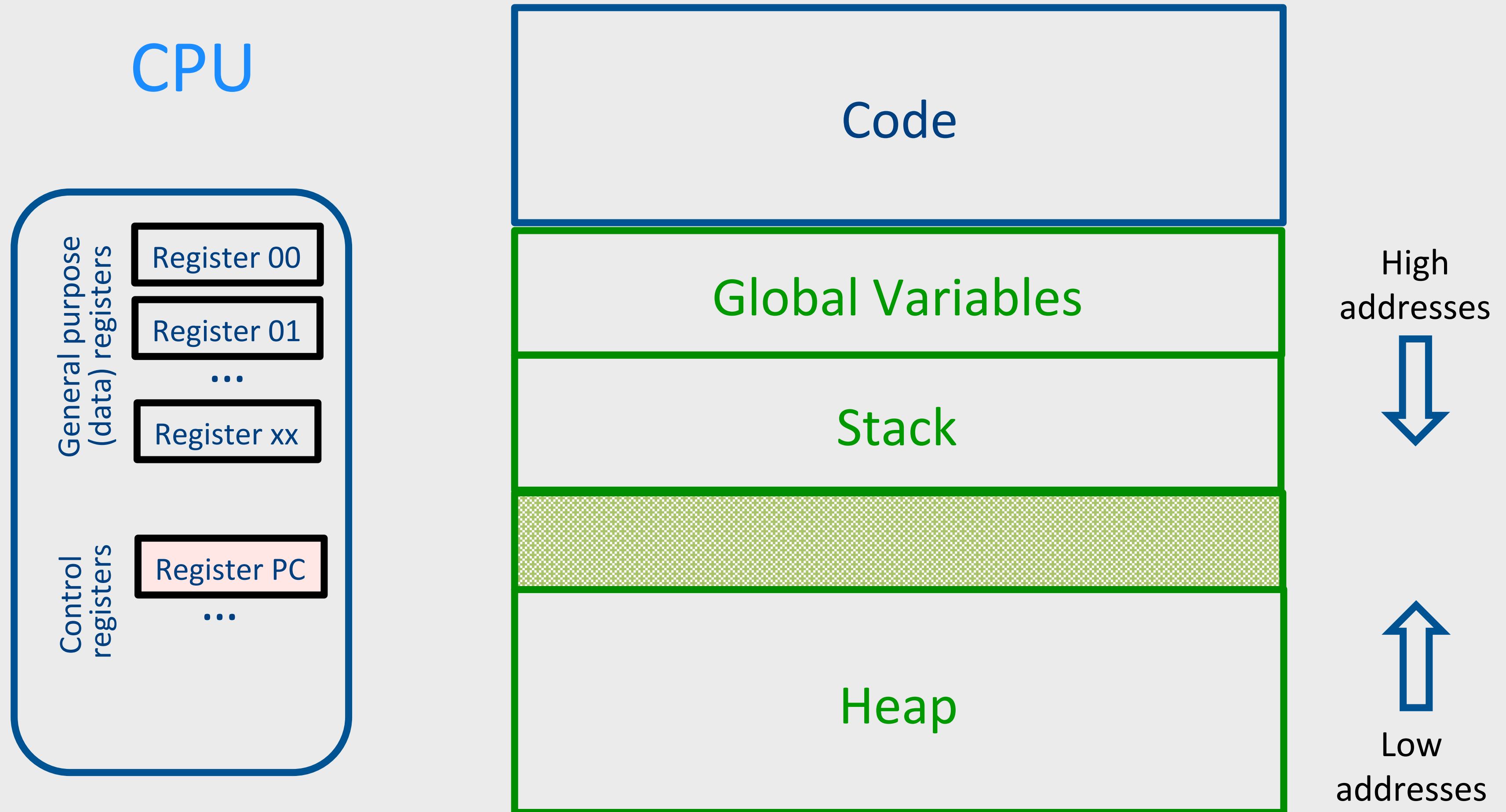
Supporting Procedures

- New computing environment
  - at least temporary memory for local variables
- Passing information into the new environment
  - Parameters
- Transfer of control to/from procedure
- Handling return values

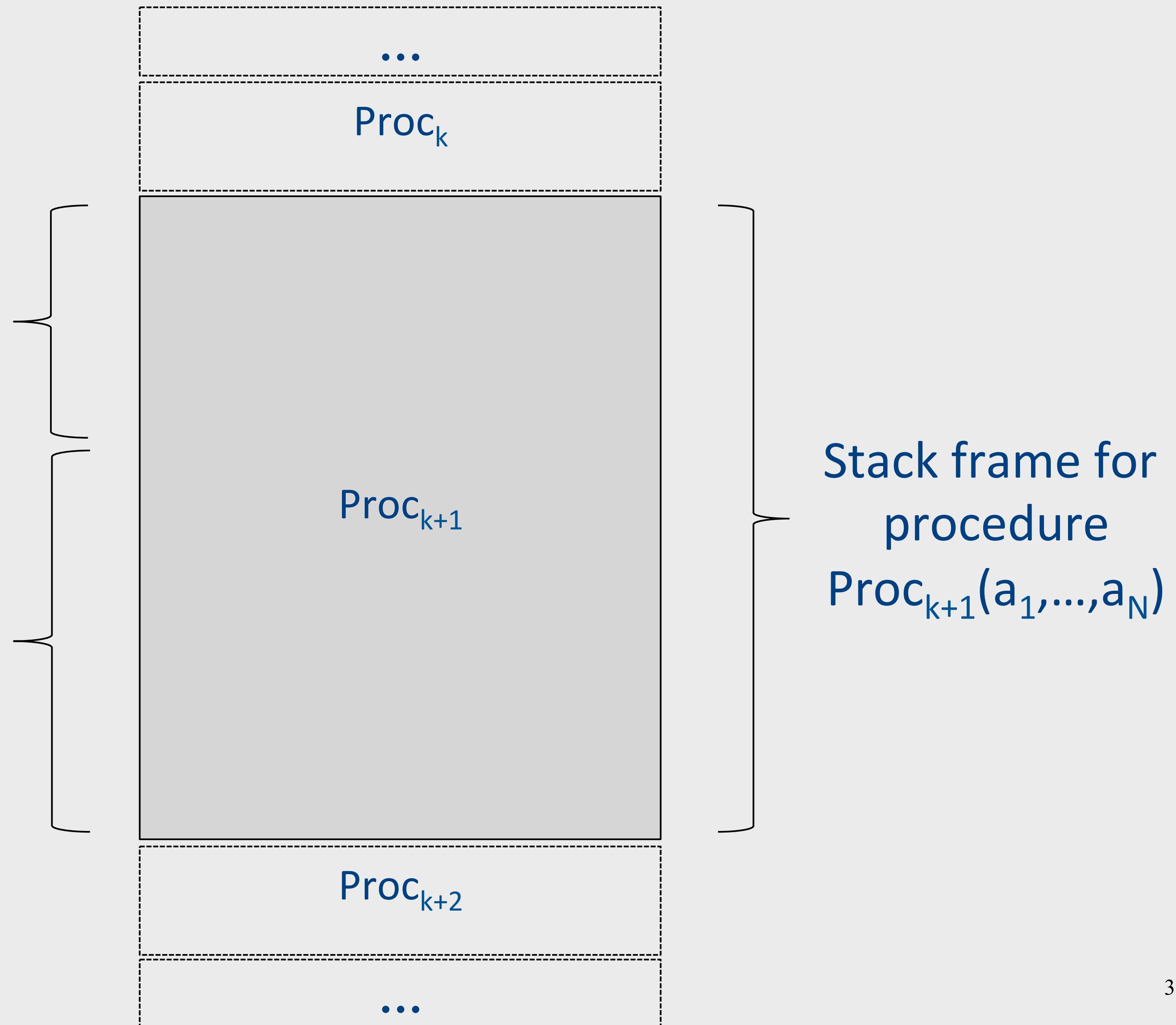
Abstract Register Machine
(High Level View)



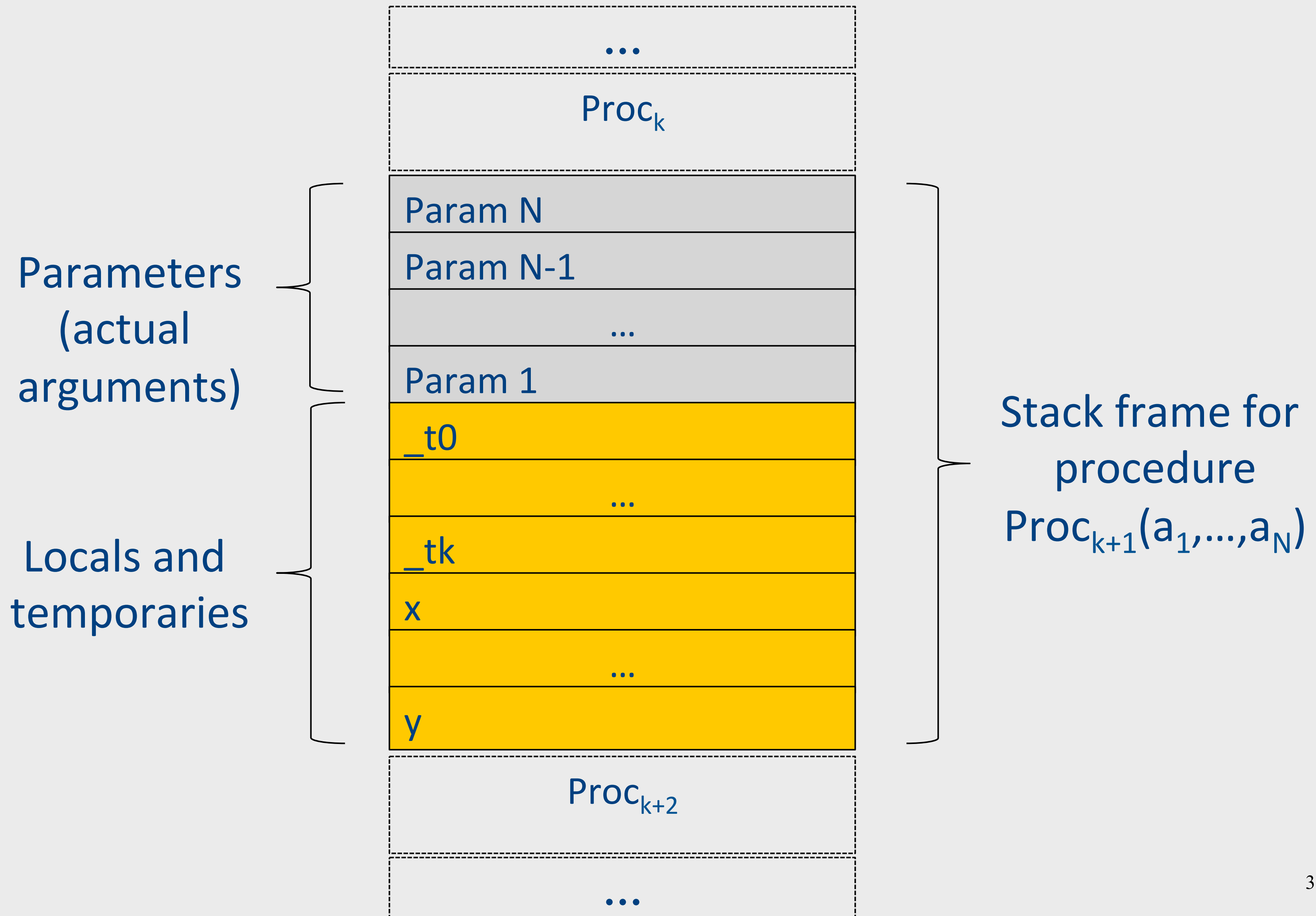
Abstract Register Machine
(High Level View)



Abstract Activation Record Stack



Abstract Stack Frame



Handling Procedures

- Store local variables/temporaries in a stack
- A function call instruction pushes arguments to stack and jumps to the function label

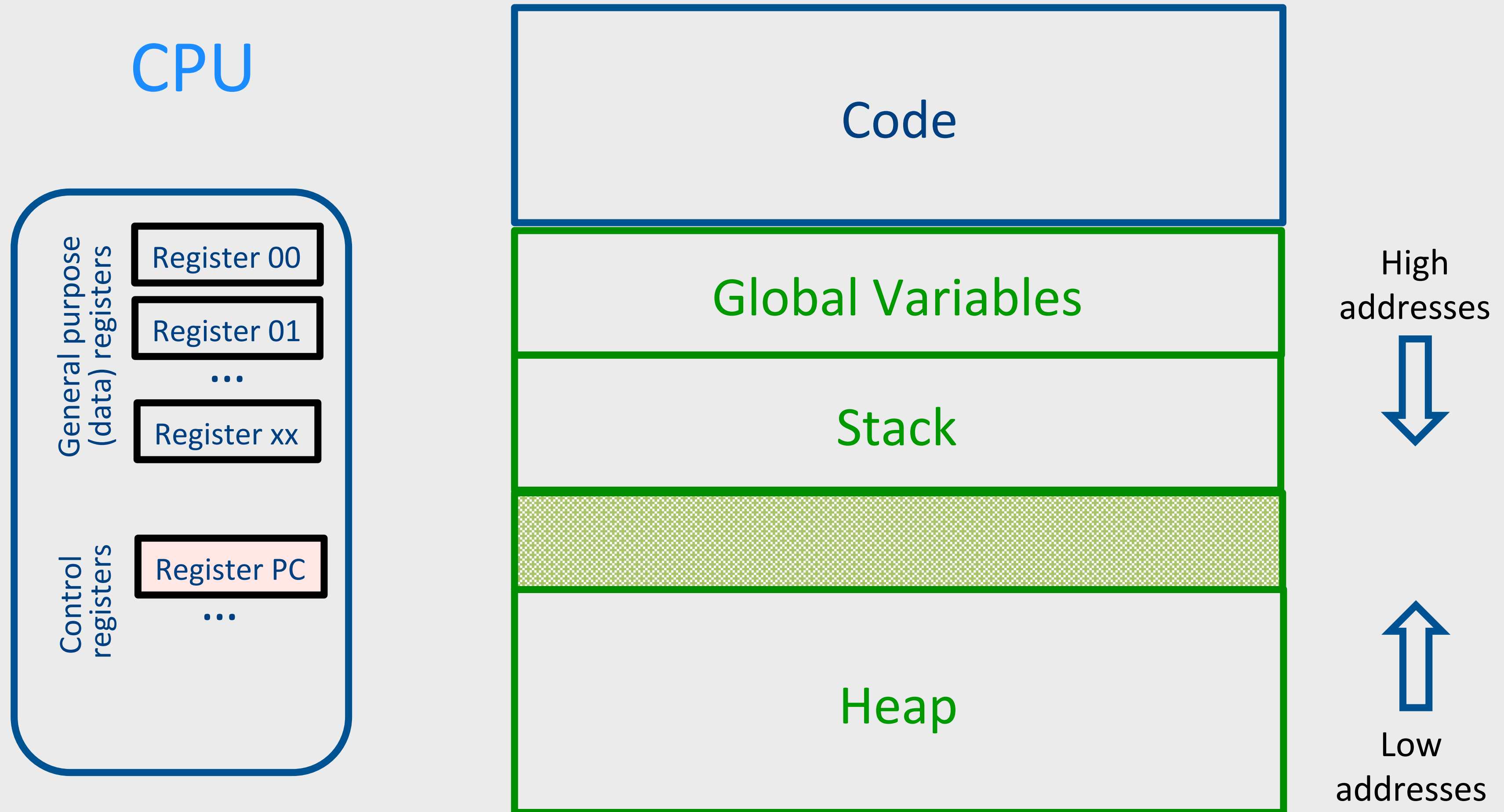
  A statement **`x=f(a1,…,an);`** looks like

  ```
  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)

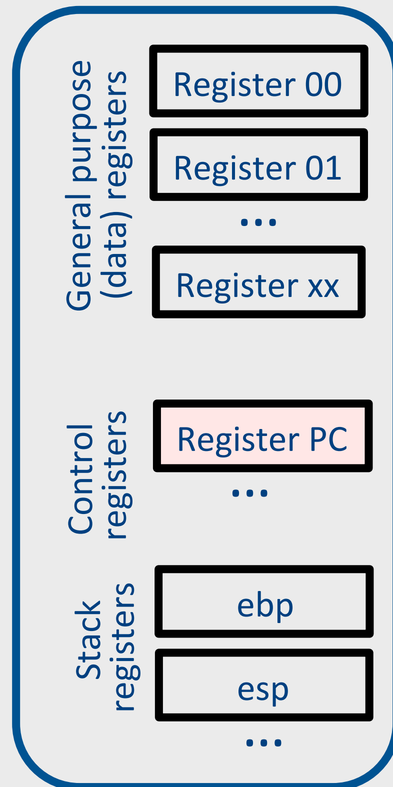
  ```
  Return;
  ```

Abstract Register Machine

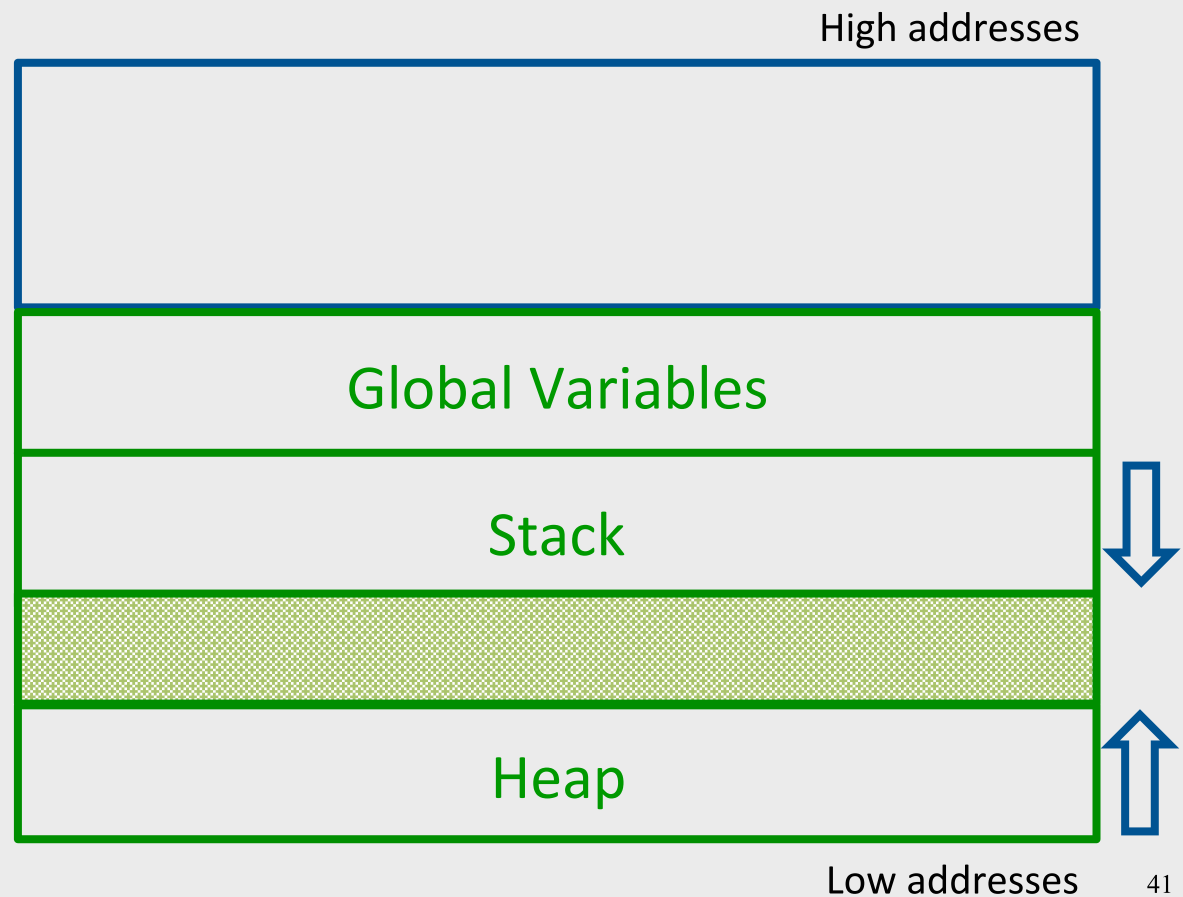


Semi-Abstract Register Machine

CPU



Main Memory



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) ;
}
```

B_0 B_1 B_2 B_3

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

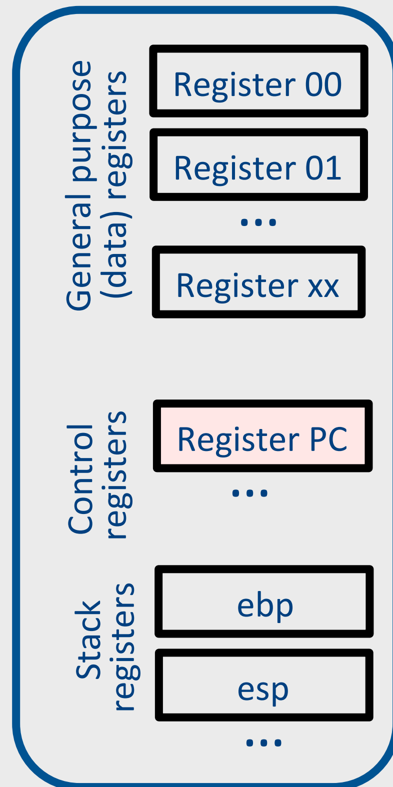
- Name
- Type
- Scope
  - when is it recognized
- Duration
  - Until when does its value exist
- Size
  - How many bytes are required at runtime
- Address
  - Fixed
  - Relative
  - Dynamic

Activation Record (Stack Frames)

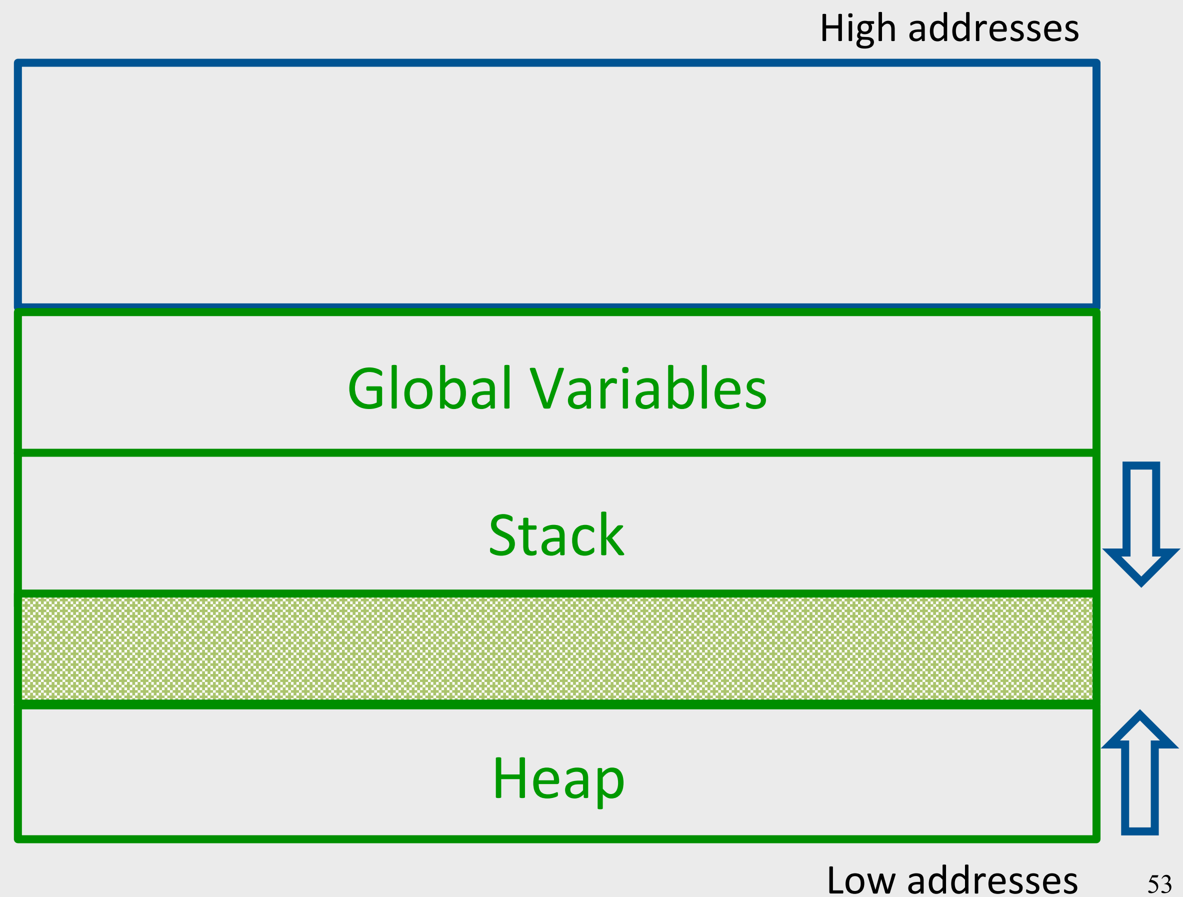
- separate space for each procedure invocation
- **managed at runtime**
  - code for managing it generated by the compiler
- desired properties
  - efficient allocation and deallocation
    - procedures are called frequently
  - variable size
    - different procedures may require different memory sizes

Semi-Abstract Register Machine

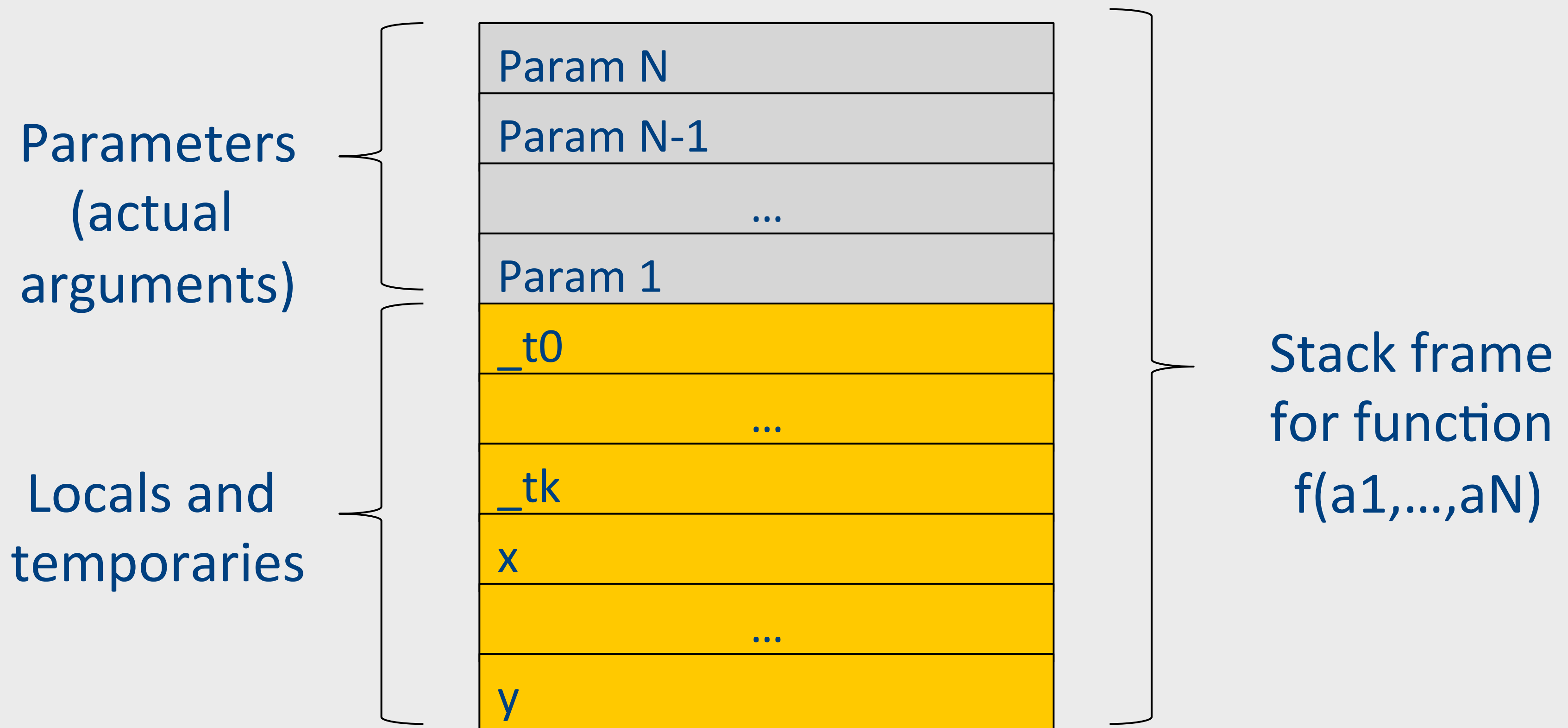
CPU



Main Memory



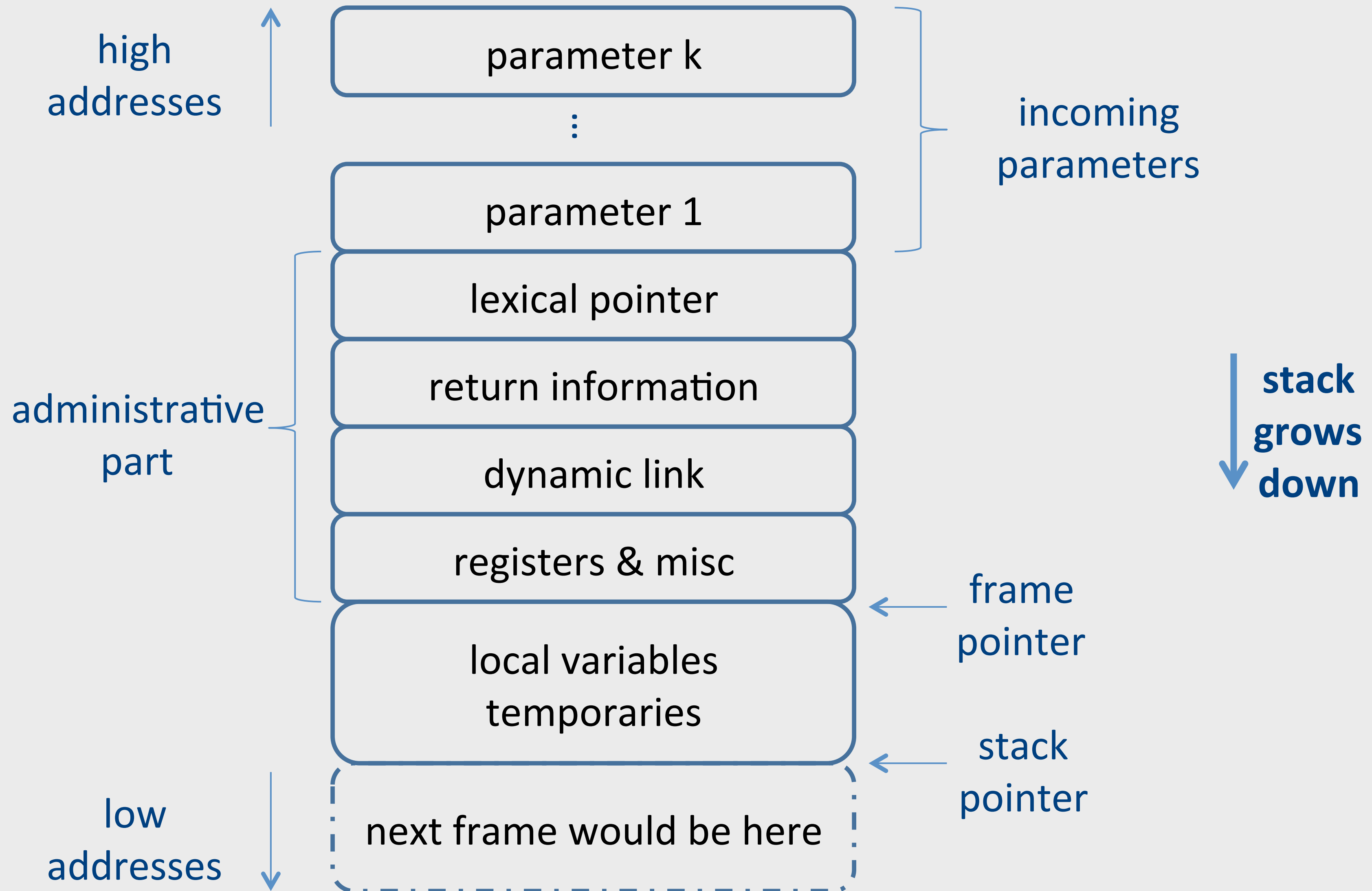
A Logical Stack Frame (Simplified)



Runtime Stack

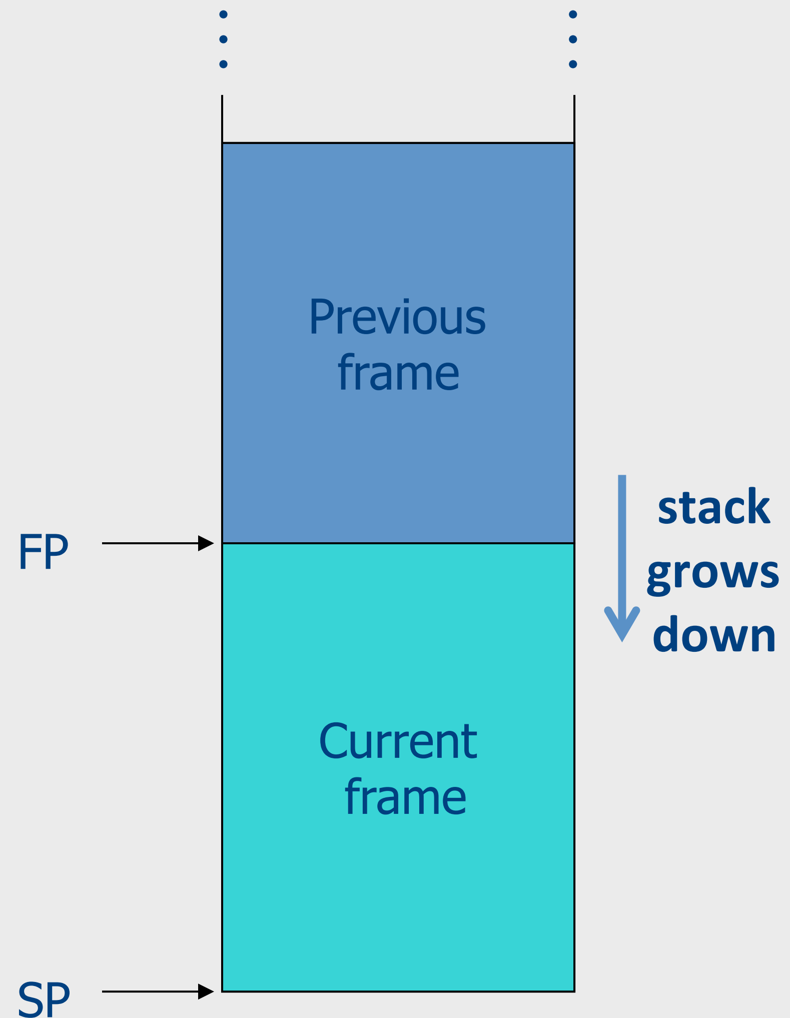
- Stack of activation records
- Call = push new activation record
- Return = pop activation record
- Only one "active" activation record – top of stack
- How do we handle recursion?

Activation Record (frame)



Runtime Stack

- SP – stack pointer
  – top of current frame
- FP – frame pointer
  – base of current frame
    – Sometimes called BP (base pointer)



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

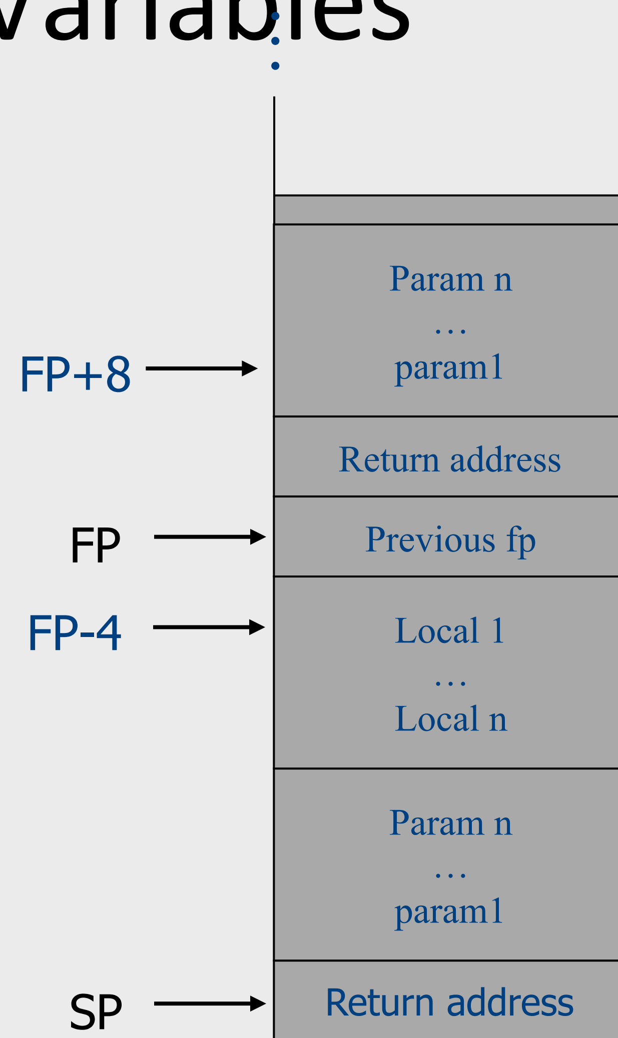
Pentium stack registers

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

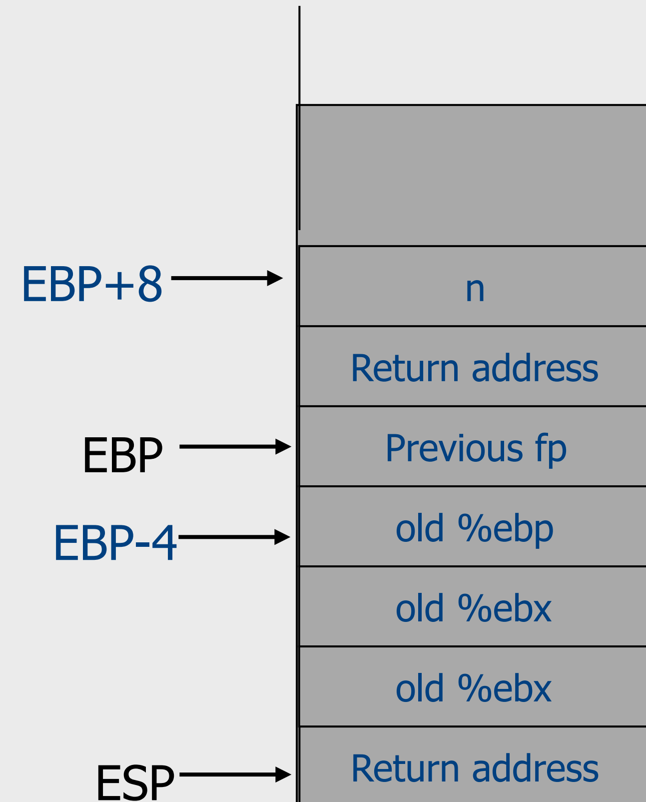
Accessing Stack Variables

- 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)

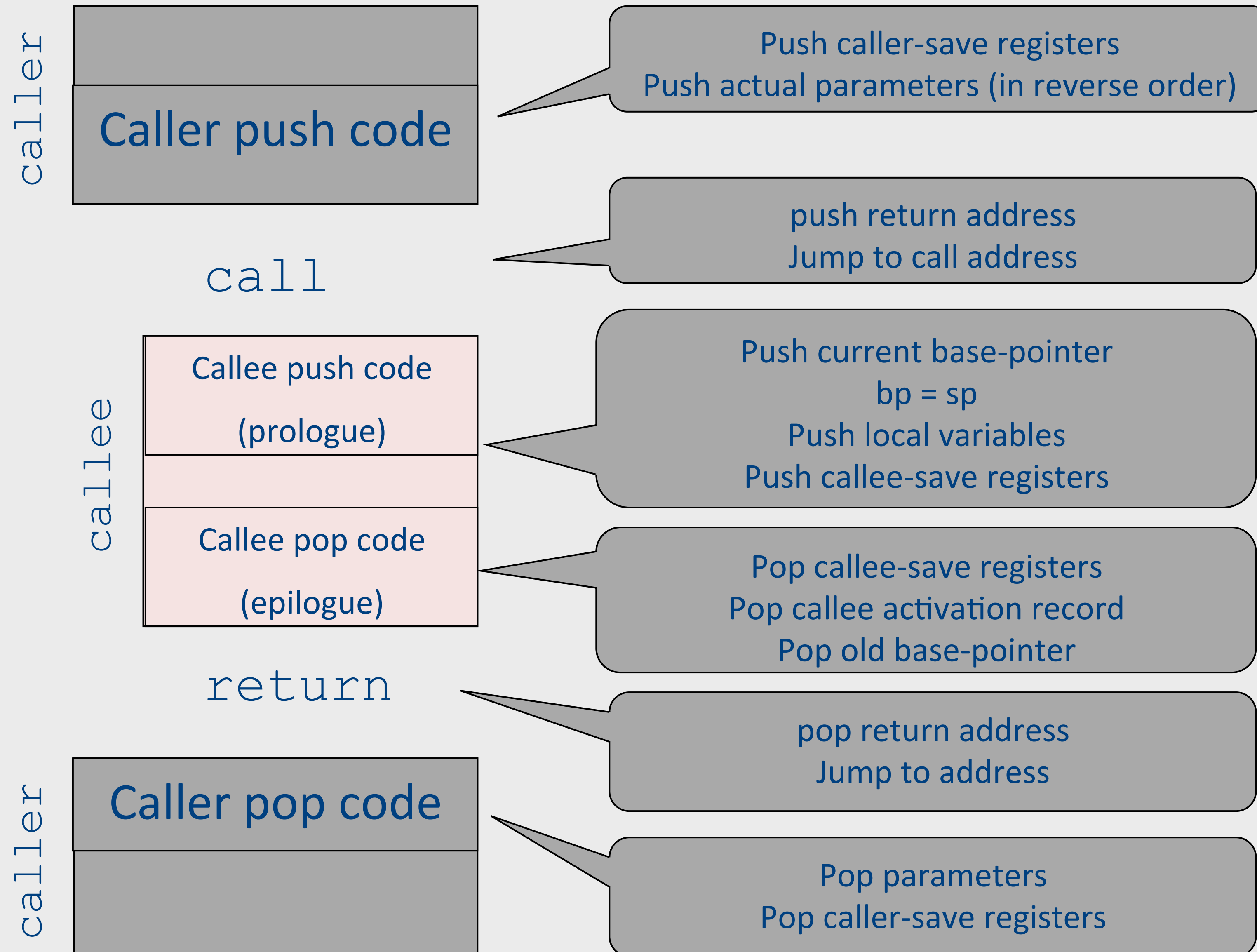
(disclaimer: real compiler can do better than that)

Call Sequences

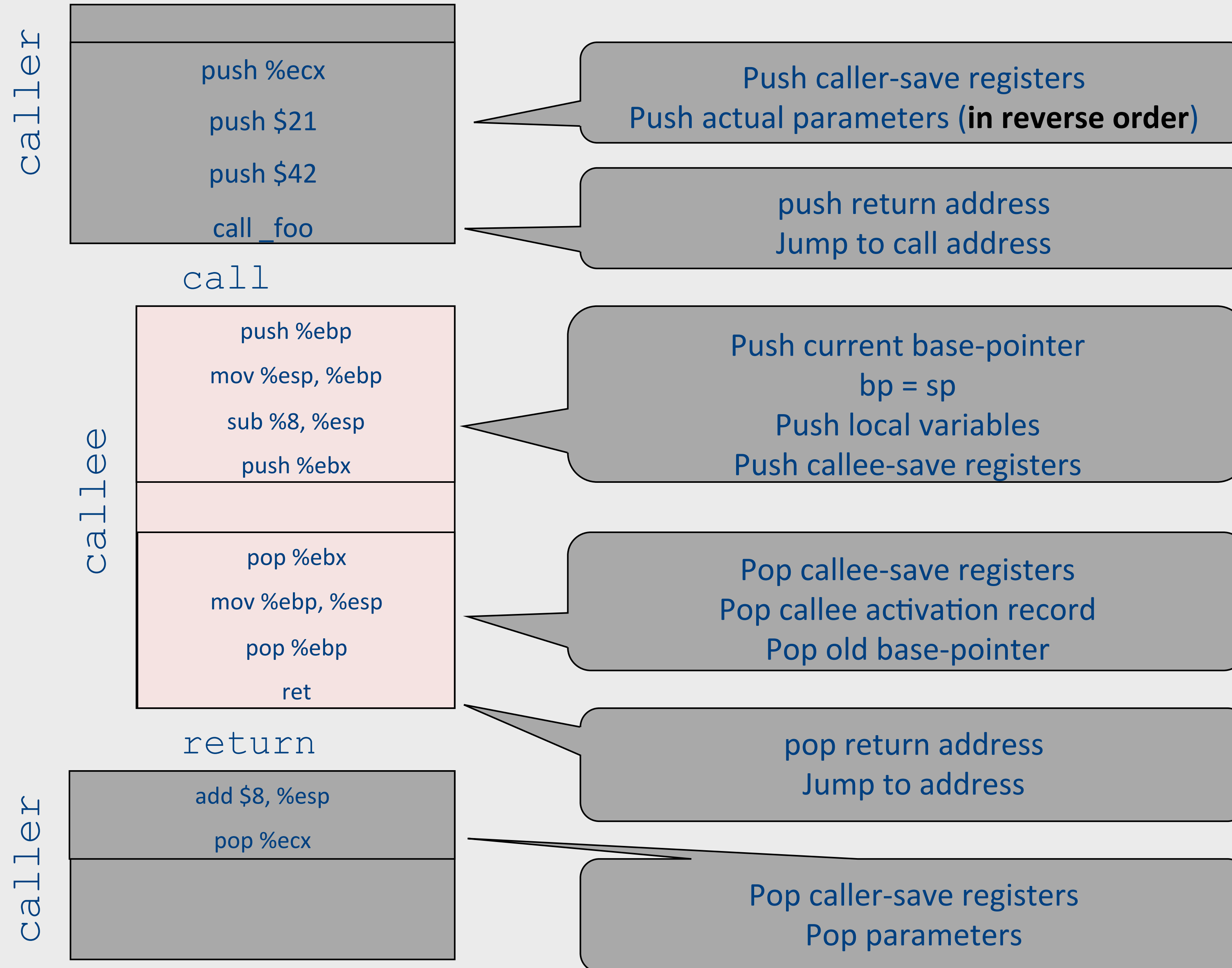
- **The processor does not save the content of registers on procedure calls**

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

Call Sequences



Call Sequences – `Foo(42,21)`



“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 calller/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
```

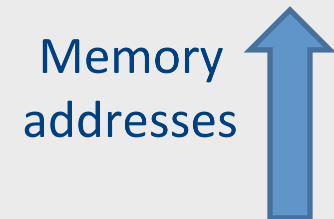
Parameter Passing

- 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?

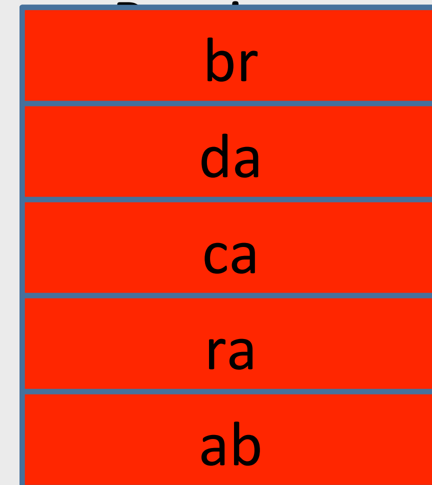
- Most procedures are leaf procedures
- Interprocedural register allocation
- Many of the registers may be dead before another invocation
- Register windows are allocated in some architectures per call (e.g., sun Sparc)

Windows Exploit(s)

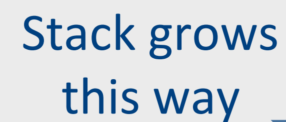
Buffer Overflow




```
void foo (char *x) {
  char buf[2];
  strcpy(buf, x);
}
int main (int argc, char *argv[]) {
  foo(argv[1]);
}
```




```
 ./a.out abracadabra
Segmentation fault
```



Buffer overflow

```
int check_authentication(char *password) {
  int auth_flag = 0;
  char password_buffer[16];

  strcpy(password_buffer, password);
  if(strcmp(password_buffer, "brillig") == 0)
          auth_flag = 1;
  if(strcmp(password_buffer, "outgrabe") == 0)
          auth_flag = 1;
   return auth_flag;
}
int main(int argc, char *argv[]) {   if(argc < 2) {
  printf("Usage: %s <password>\n", argv[0]); exit(0);     }
  if(check_authentication(argv[1])) {
     printf("\n-=-=-=-=-=-=-=-=-=-=-=-=-=-\n");
     printf("      Access Granted.\n");
     printf("-=-=-=-=-=-=-=-=-=-=-=-=-=-\n");   }
  else {
     printf("\nAccess Denied.\n");
   }
}
```

(source: "hacking – the art of exploitation, 2nd Ed")

Buffer overflow

```
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   char password_buffer[16];

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     printf("     Access Granted.\n");
     printf("-=-=-=-=-=-=-=-=-=-=-=-=-=-\n");  }
  else {
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   }
}
```

(source: “hacking – the art of exploitation, 2nd Ed”)

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   return auth_flag;
}
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  if(check_authentication(argv[1])) {
     printf("\n-=-=-=-=-=-=-=-=-=-=-=-=-=-\n");
     printf("      Access Granted.\n");
     printf("-=-=-=-=-=-=-=-=-=-=-=-=-=-\n");   }
   else {
      printf("\nAccess Denied.\n");
   }
}
```

(source: “hacking – the art of exploitation, 2nd Ed”)

Buffer overflow

```
0x08048529 <+69>:   movl   $0x8048647,(%esp)
0x08048530 <+76>:   call   0x8048394 <puts@plt>
0x08048535 <+81>:   movl   $0x8048664,(%esp)
0x0804853c <+88>:   call   0x8048394 <puts@plt>
0x08048541 <+93>:   movl   $0x804867a,(%esp)
0x08048548 <+100>:  call   0x8048394 <puts@plt>
0x0804854d <+105>:  jmp    0x804855b <main+119>
0x0804854f <+107>:  movl   $0x8048696,(%esp)
0x08048556 <+114>:  call   0x8048394 <puts@plt>
```

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

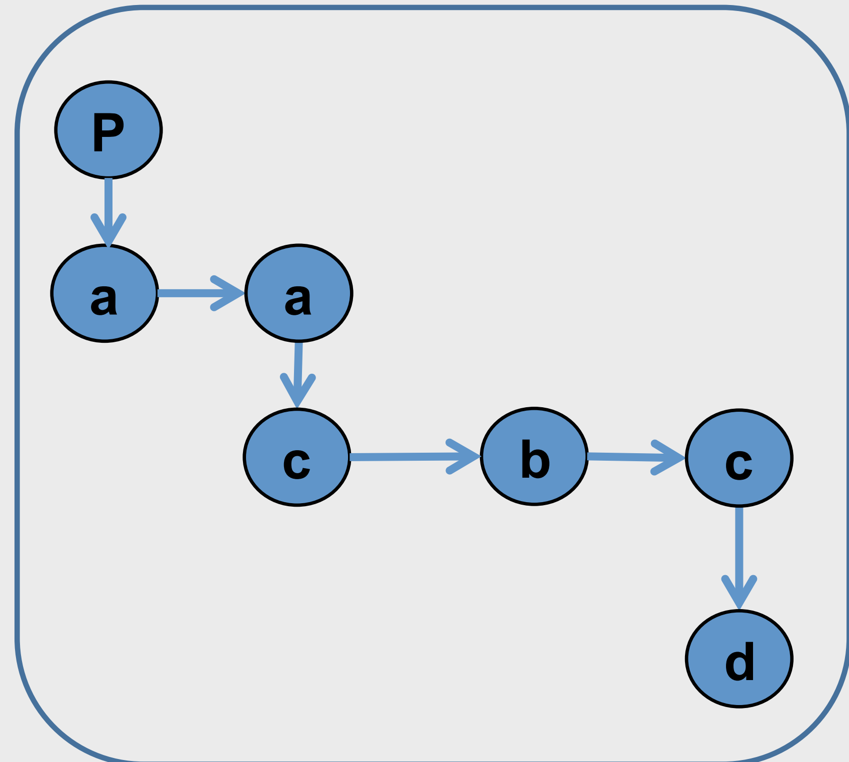
what are the addresses of variables “x,” “y” and “z” in procedure d?

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?

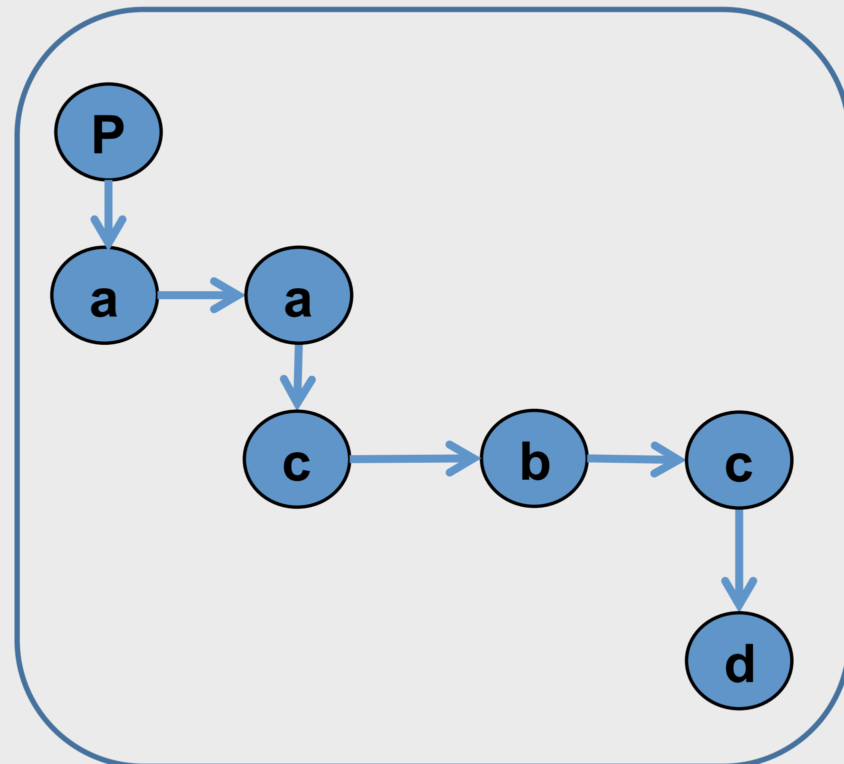
Possible call sequence:
p → a → a → c → b → c → d



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



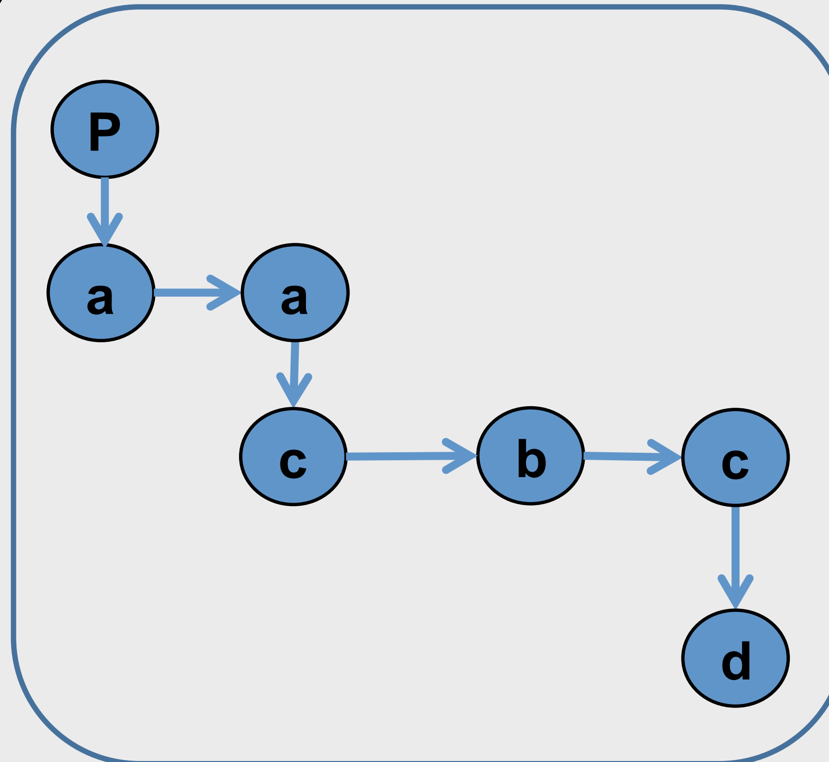
Nested Procedures

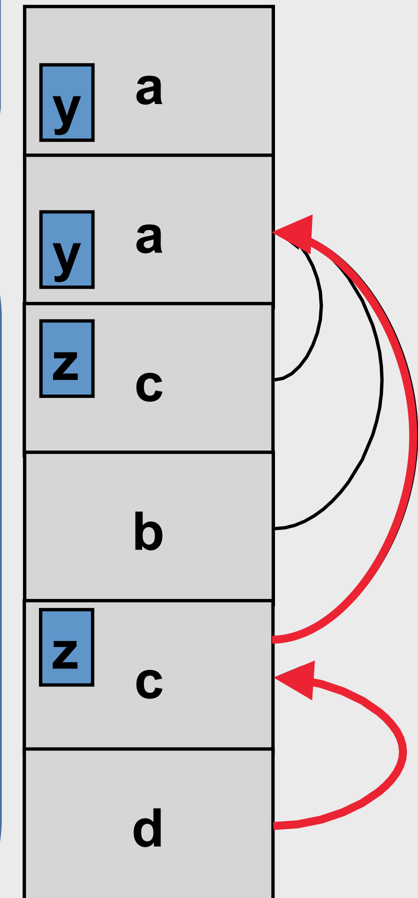
- problem: a routine may need to access variables of another routine that contains it statically
- solution: lexical pointer (a.k.a. access link) in the activation record
- lexical pointer points to the last activation record of the nesting level above it
  - in our example, lexical pointer of d points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

Lexical Pointers

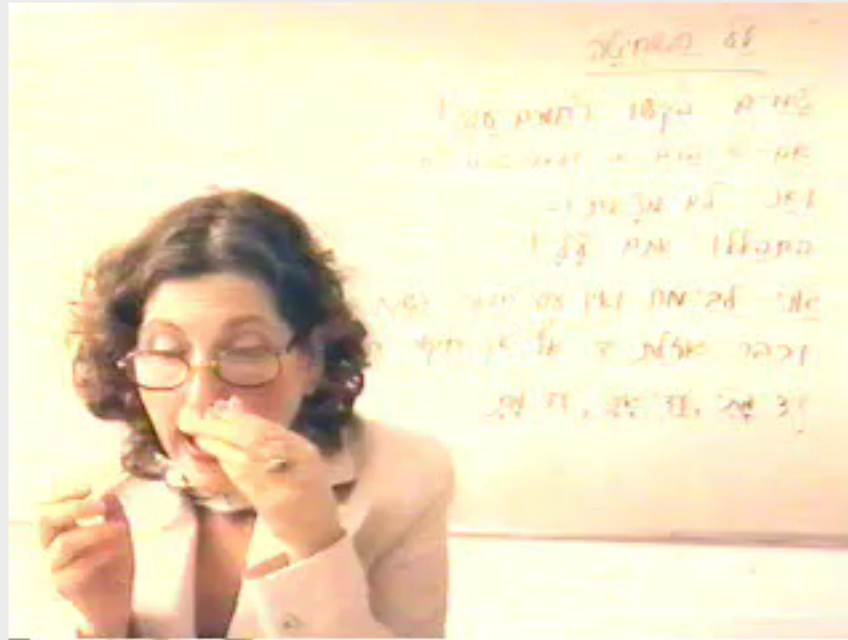
```
program p(){
  int x;
  procedure a(){
    int y;
    procedure b(){ c() };
    procedure c(){
      int z;
      procedure d(){
        y := x + z
      };
      … b() … d() …
    }
    … a() … c() …
  }
  a()
}
```

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

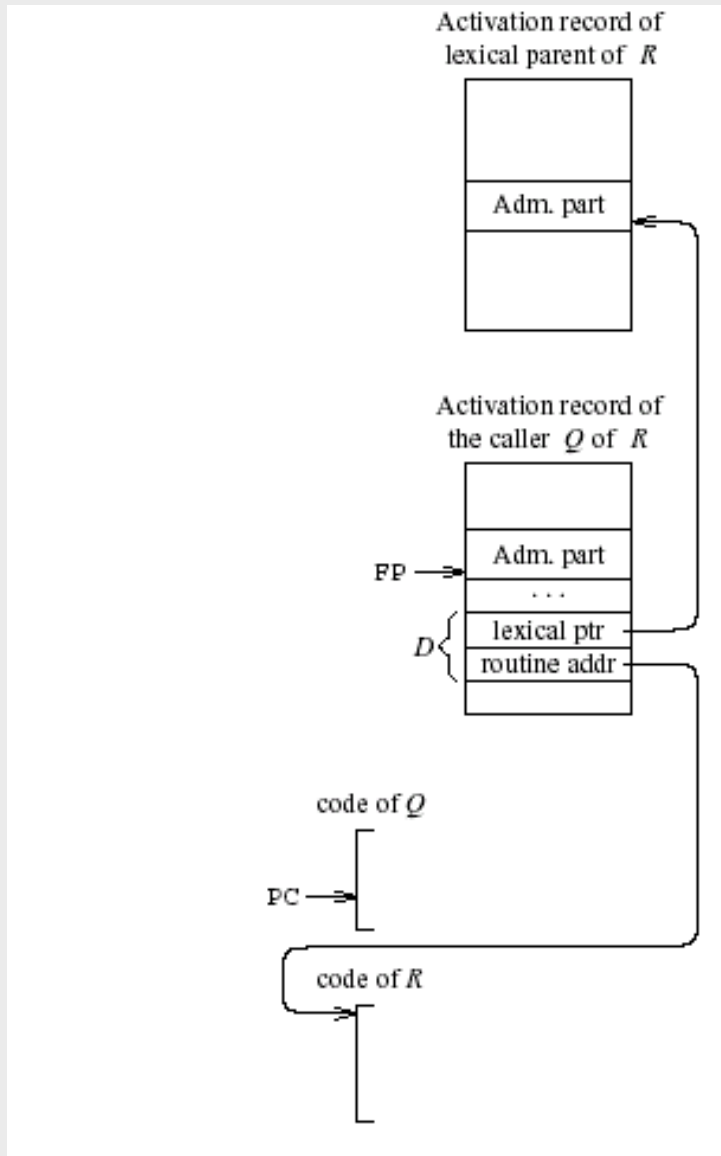


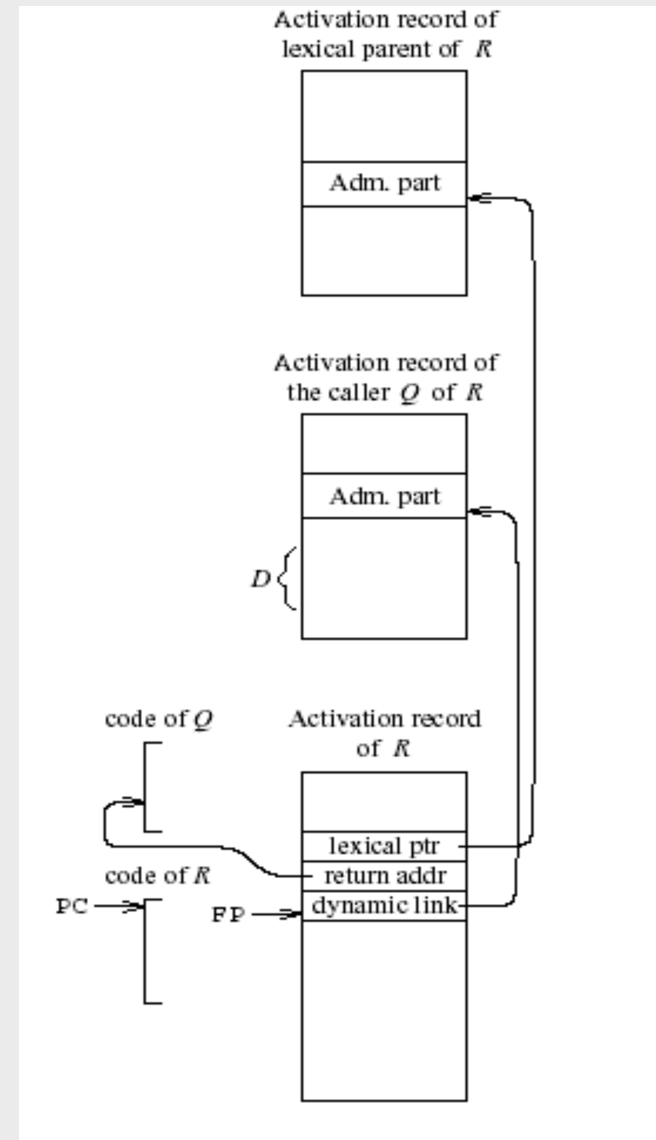


What is a Compiler?



Procedure Q Calls R





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 ;
}
```

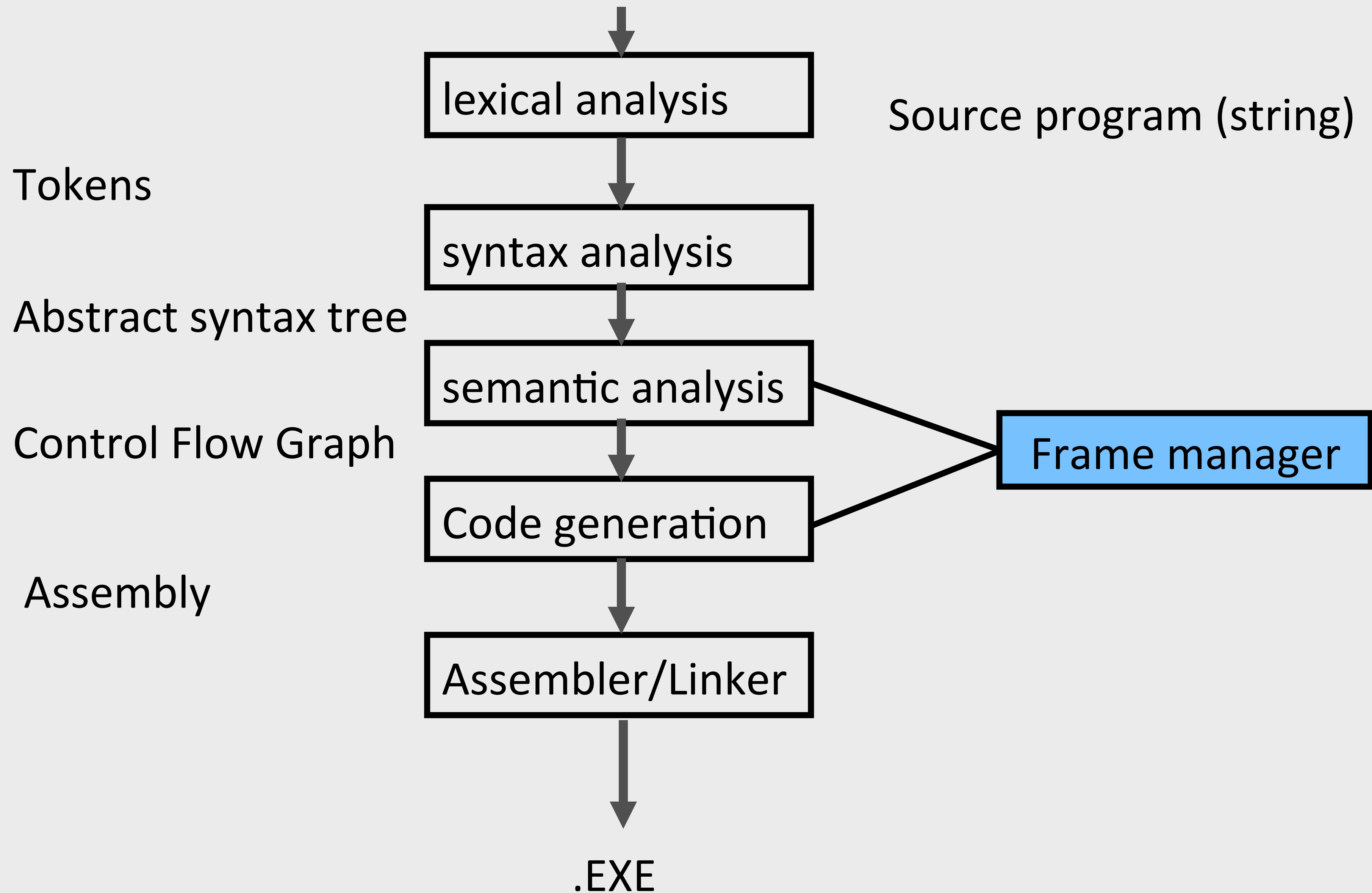
- Example 3: Dynamic allocation

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

Compiler Implementation

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

Basic Compiler Phases



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

Invocations to Frame

- “Allocate” a new frame
- “Allocate” new local variable
- Return the L-value of local variable
- Generate code for procedure invocation
- Generate prologue/epilogue
- Generate code for procedure return

Activation Records: Summary

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

The End