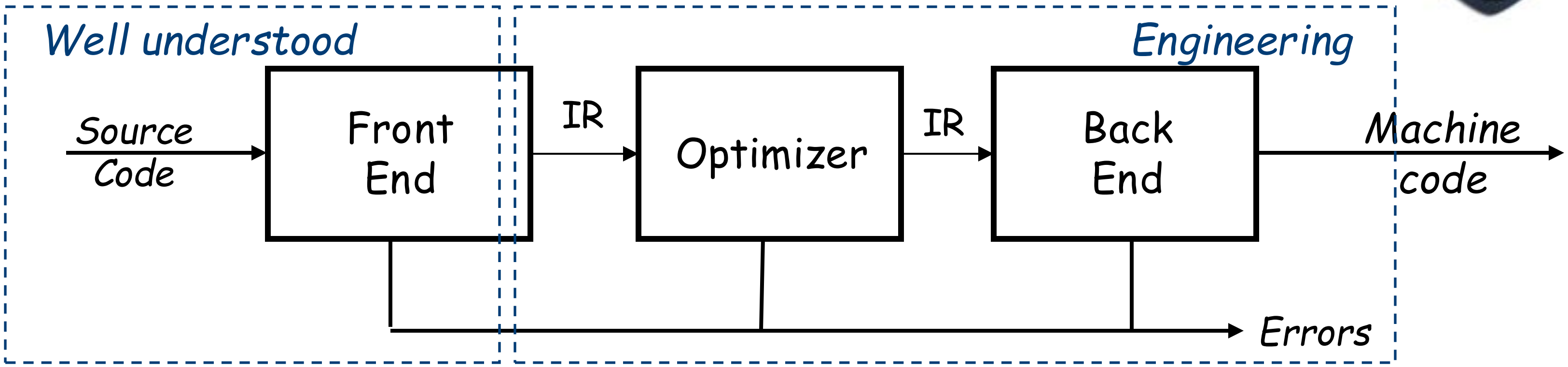
COMP 412
FALL 2010

The Procedure Abstraction
Comp 412

Chapters 6 and 7 of EaC explore techniques that compilers use to implement various language features.

Where are we?



The latter half of a compiler contains more open problems, more challenges, and more gray areas than the front half

- This is "compilation," as opposed to "parsing" or "translation"
- Implementing promised behavior
  – Defining and preserving the meaning of the program
- Managing target machine resources
  – Registers, memory, issue slots, locality, power, …
  – These issues determine the quality of the compiled code

Conceptual Overview

The compiler must provide, for each programming language construct, an implementation (or at least a strategy).

Those constructs fall into two major categories
- Individual statements
- Procedures

We will look at procedures first, since they provide the surrounding context needed to implement statements

Object-oriented languages add some peculiar twists
- We will treat OOL features in a separate lecture or two

In EaC, Chapter 6 covers implementation of procedures & Chapter 7 covers statements.

Conceptual Overview

Procedures provide the fundamental abstractions that make programming practical & large software systems possible

- Information hiding
- Distinct and separable name spaces
- Uniform interfaces

Hardware does little to support these abstractions

- Part of the compiler's job is to implement them
  - *Compiler makes good on lies that we tell programmers*
- Part of the compiler's job is to make it efficient
  - *Role of code optimization*

Practical Overview

The compiler must decide almost everything

- Location for each value (named and unnamed)
- Method for computing each result
  - *For example, how should it compute y^x or a case statement?*
- Compile-time versus runtime behavior
- How to locate objects & values created & manipulated by code that the compiler cannot see? (*other files, libraries*)
  - *Dynamic loading and linking add more complications*

All of these issues come to the forefront when we consider the implementation of procedures

Pay close attention to compile-time versus runtime

- *Confuses students more than any other issue*

The Procedure Abstraction

The compiler must deal with interface between compile time and run time (*static* versus *dynamic*)

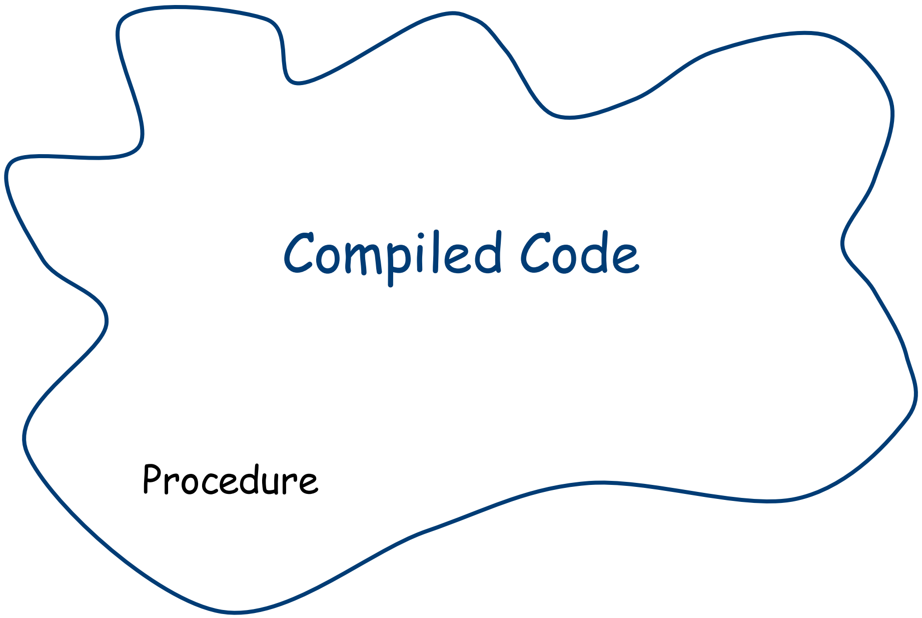
- Most of the tricky issues arise in implementing "procedures"

Issues

- Compile-time versus run-time behavior
- Assign storage for <u>everything</u> & map names to addresses
- Generate code to address any value
  - *Compiler knows where some of them are*
  - *Compiler cannot know where others are*
- Interfaces with other programs, other languages, & the OS
- Efficiency of implementation

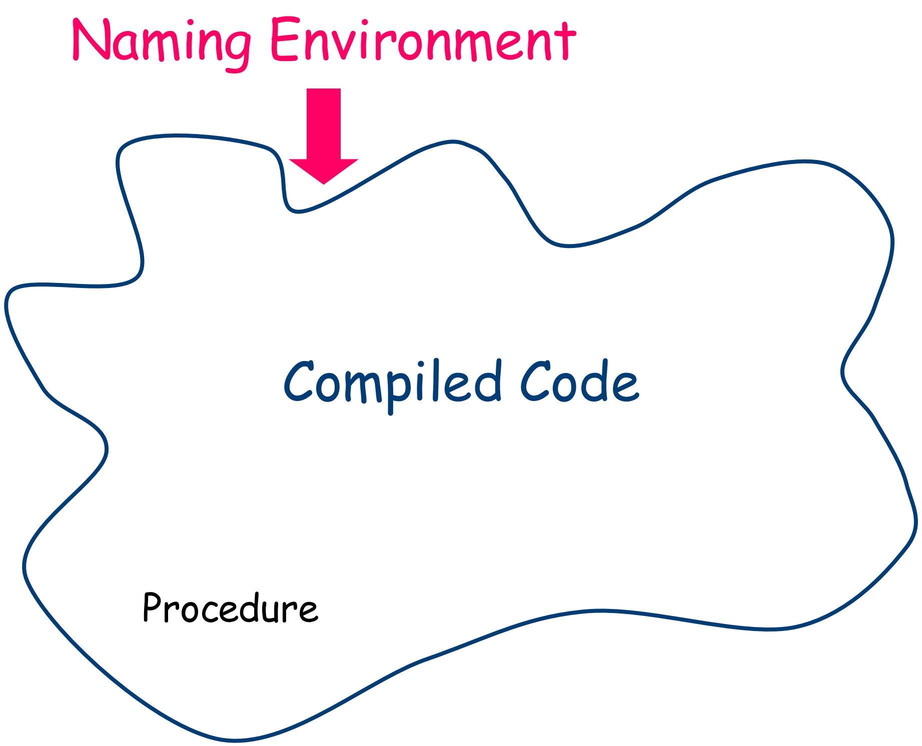
The Procedure & Its Three Abstractions

The compiler produces code for each procedure



The individual code bodies must fit together to form a working program

The Procedure & Its Three Abstractions



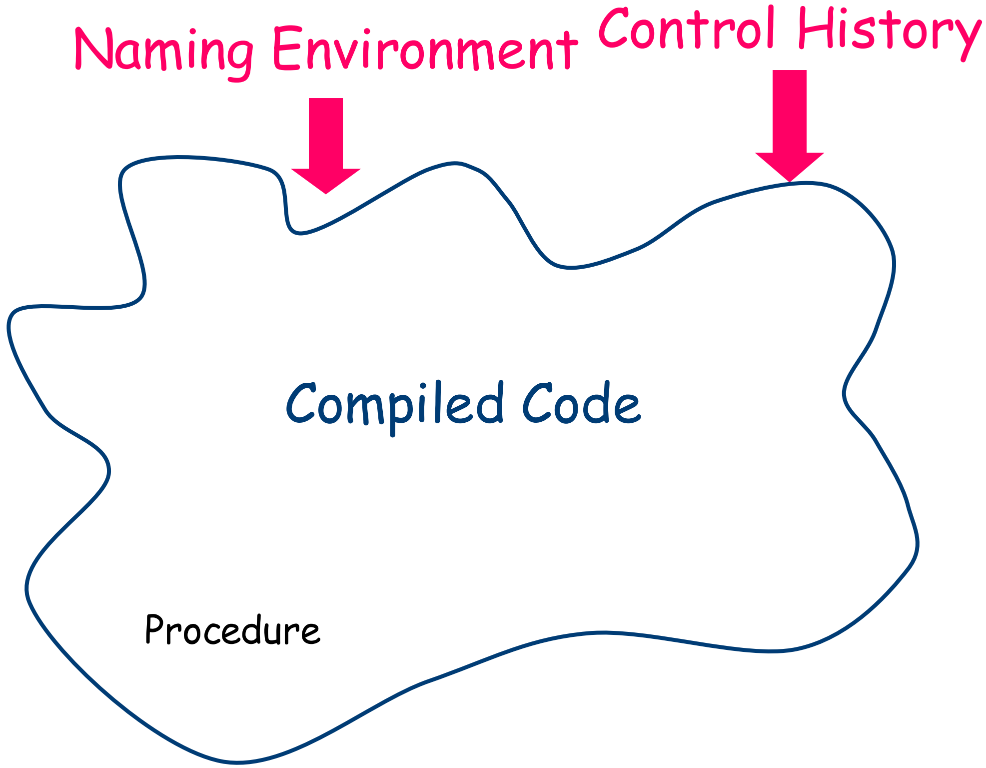
"Naming" includes the ability to find and access objects in memory

Each procedure inherits a set of names

⇒ Variables, values, procedures, objects, locations, …

⇒ Clean slate for new names, "scoping" can hide other names

The Procedure & Its Three Abstractions



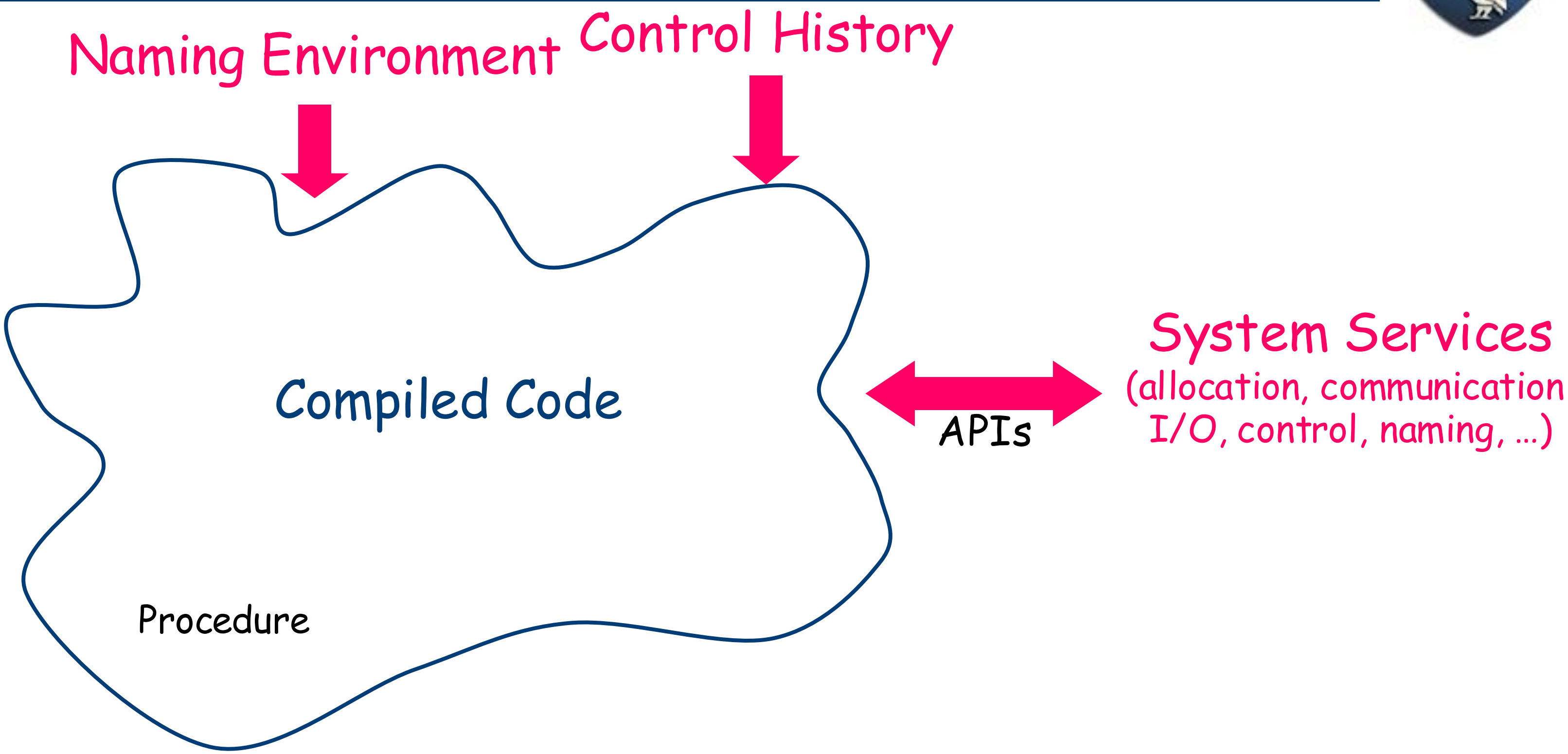
Each procedure inherits a control history

⇒ Chain of calls that led to its invocation

⇒ Mechanism to return control to caller

Some notion of parameterization (ties back to naming)

The Procedure & Its Three Abstractions



Each procedure has access to external interfaces

⇒ Access by name, with parameters *(may include dynamic link & load)*

⇒ Protection for both sides of the interface

The Procedure: Three Abstractions

- Control Abstraction
  - Well defined entries & exits
  - Mechanism to return control to caller
  - Some notion of parameterization (usually)
- Clean Name Space
  - Clean slate for writing locally visible names
  - Local names may obscure identical, non-local names
  - Local names cannot be seen outside
- External Interface
  - Access is by procedure name & parameters
  - Clear protection for both caller & callee
  - Invoked procedure can ignore calling context

Procedures permit a critical separation of concerns

The Procedure (Realist's View)

Procedures are the key to building large systems

- Requires system-wide compact
  - Conventions on memory layout, protection, resource allocation calling sequences, & error handling
  - Must involve architecture (**ISA**), **OS**, & compiler
- Provides shared access to system-wide facilities
  - Storage management, flow of control, interrupts
  - Interface to input/output devices, protection facilities, timers, synchronization flags, counters, …
- Establishes a private context
  - Create private storage for each procedure invocation
  - Encapsulate information about control flow & data abstractions

The Procedure (Realist's View)

Procedures allow us to use separate compilation

- Separate compilation allows us to build non-trivial programs
- Keeps compile times reasonable
- Lets multiple programmers collaborate
- Requires independent procedures

Without separate compilation, we *would not* build large systems

The procedure linkage convention

- Ensures that each procedure inherits a valid run-time environment and that the callers environment is restored on return
  - The compiler must generate code to ensure this happens according to conventions established by the system

The Procedure (More Abstract View)

A procedure is an abstract structure constructed via software

Underlying hardware directly supports little of the abstraction—it understands bits, bytes, integers, reals, & addresses, but not:

- Entries and exits
- Interfaces
- Call and return mechanisms
  - Typical machine supports the transfer of control (call and return) but not the rest of the calling sequence (*e.g.*, preserving context)
- Name space
- Nested scopes

All these are established by carefully-crafted mechanisms provided by compiler, run-time system, linker, loader, and OS;

The compiler's job is to make good on the lies told by the programming language design!

Run Time versus Compile Time

These concepts are often confusing to the newcomer

- Linkages (*and code for procedure body*) execute at run time
- Code for the linkage is emitted at compile time
- The linkage is designed long before either of these

This issue (compile time versus run time) confuses students more than *any other* issue in Comp 412

- We will emphasize the distinction between them

The Procedure as a Control Abstraction

Procedures have well-defined control-flow

The Algol-60 procedure call

- Invoked at a call site, with some set of *actual parameters*
- Control returns to call site, immediately after invocation

```
...
s = p(10,t,u);
...
```

```
int p(a,b,c)
   int a, b, c;
{
  int   d;
  d = q(c,b);
  ...
}
```

```
int q(x,y)
   int x,y;
{
   if ( ... )
      x = q(x-1,y);
   return x + y;
}
```

- Most languages allow recursion

The Procedure as a Control Abstraction

Implementing procedures with this behavior

- Requires code to save and restore a "return address"
- Must map actual parameters to formal parameters   ($c \rightarrow x$, $b \rightarrow y$)
- Must create storage for local variables (&, maybe, parameters)
  - *p* needs space for *d* (&, maybe, *a*, *b*, & *c*)
  - where does this space go in recursive invocations?

```
...
s = p(10,t,u);
...
```

```
int p(a,b,c)
   int a, b, c;
{
  int   d;
  d = q(c,b);
  ...
}
```

```
int q(x,y)
   int x,y;
{
   if ( ... )
     x = q(x-1,y);
   return x + y;
}
```

Compiler emits code that causes all this to happen at run time

The Procedure as a Control Abstraction

Implementing procedures with this behavior

- Must preserve *p*'s state while *q* executes
  - recursion causes the real problem here
- *Strategy:* Create unique location for each procedure activation
  - In simple situations, can use a "stack" of memory blocks to hold local storage and return addresses (*closures ⇒ heap allocate*)

```
...
s = p(10,t,u);
...
```

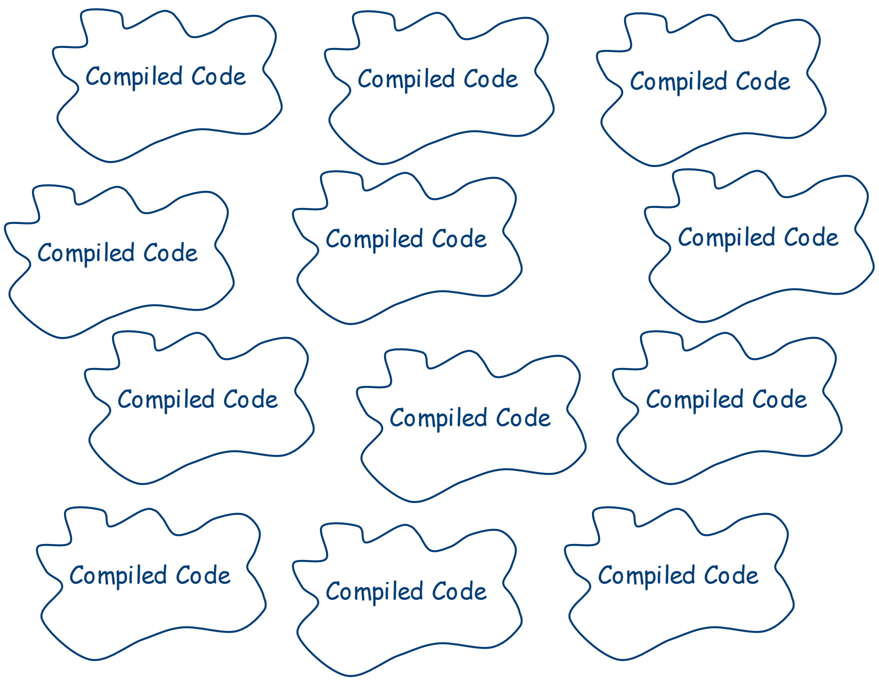
```
int p(a,b,c)
   int a, b, c;
{
   int  d;
   d = q(c,b);
   ...
}
```

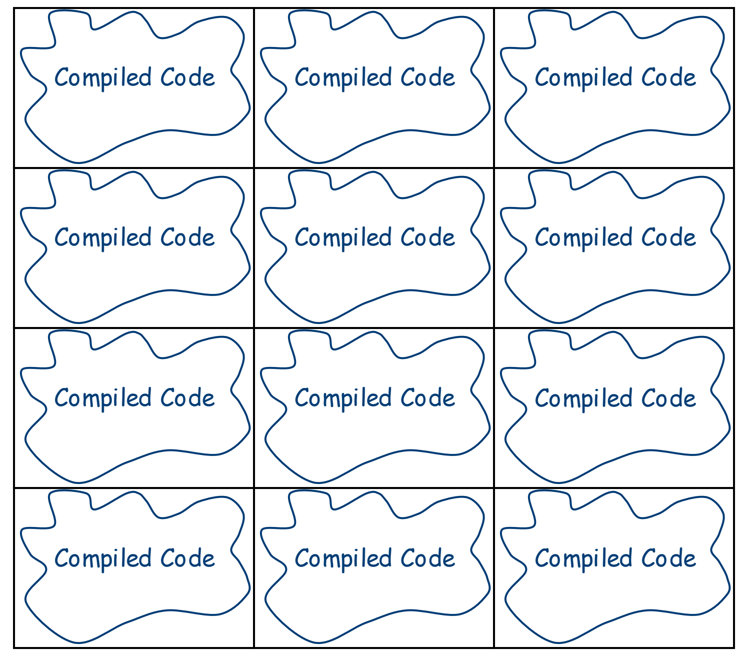
```
int q(x,y)
   int x,y;
{
   if ( ... )
      x = q(x-1,y);
   return x + y;
}
```

Compiler emits code that causes all this to happen at run time

The Procedure as a Control Abstraction

In essence, the procedure linkage wraps around the unique code of each procedure to give it a uniform interface





Similar to building a brick wall rather than a rock wall

STOP

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The Procedure Abstraction: Part II

Comp 412

Review

From last lecture

The Procedure serves as

- A control abstraction
- A naming abstraction
- An external interface

Access to system services, libraries, code from others …

We covered the control abstraction last lecture.

Today, we will focus on naming.

The Procedure as a Name Space

Each procedure creates its own name space

The Java twist: allow fully qualified names to reach around scope rules

- Any name (almost) can be declared locally
- Local names obscure identical non-local names
- Local names cannot be seen outside the procedure
  - Nested procedures are "inside" by definition
- We call this set of rules & conventions "lexical scoping"

Examples

- C has global, static, local, and *block* scopes *(Fortran-like)*
  - Blocks can be nested, procedures cannot
- Scheme has global, procedure-wide, and nested scopes *(let)*
  - Procedure scope (typically) contains formal parameters

The Procedure as a Name Space

Why introduce lexical scoping?

- Provides a compile-time mechanism for binding "free" variables
- Simplifies rules for naming & resolves conflicts
- Lets the programmer introduce "local" names with impunity

How can the compiler keep track of all those names?

The Problem

- At point *p*, which declaration of *x* is current?
- At run-time, where is *x* found?
- As parser goes in & out of scopes, how does it delete *x*?

The Answer

- The compiler must model the name space
- Lexically scoped symbol tables (see § 5.7 in EaC 1e)

Do People Use This Stuff ?

C macro from the MSCP compiler

```
#define fix_inequality(oper, new_opcode)                \
    if (value0 < value1)                                \
    {                                                   \
        Unsigned_Int temp = value0;                     \
        value0 = value1;                                \
        value1 = temp;                                  \
        opcode_name = new_opcode;                       \
        temp = oper->arguments[0];                      \
        oper->arguments[0] = oper->arguments[1];        \
        oper->arguments[1] = temp;                      \
        oper->opcode = new_opcode;                      \
    }
```

Even in C, a language not known for abstraction, people use scopes to hide details!

Declares a new name "temp"

Do People Use This Stuff ?

Of course, it might have been more clear written as:

```
#define swap_values( val0, val1 )                \
   {                                             \
     Unsigned_Int tem = val0;                    \
     val0 = val1;                                \
     val1 = temp;                                \
   }

#define fix_inequality(oper, new_opcode)  \
   if (value0 < value1)                          \
   {                              \
      swap_values( val0, val1 );                 \
      opcode_name = new_opcode;          \
      temp = oper->arguments[0];          \
      oper->arguments[0] = oper->arguments[1];  \
      oper->arguments[1] = temp;          \
      oper->opcode = new_opcode;          \
   }
```

Even in C, we can build abstractions that are useful and tasteful.

§ 5.7 in EaC 1e

Lexically-scoped Symbol Tables

The problem

- The compiler needs a distinct record for each declaration
- Nested lexical scopes admit duplicate declarations

The interface

- insert(*name*, *level*) – creates record for *name* at *level*
- lookup(*name*, *level*) – returns pointer or index
- delete(*level*) – removes all names declared at *level*

Many implementation schemes have been proposed

- We'll stay at the conceptual level
- Hash table implementation is tricky, detailed, & (yes) fun
  - Good alternatives exist (*multiset discrimination, acyclic DFAs*)

Symbol tables are compile-time structures that the compiler uses to resolve references to names. We'll see the corresponding run-time structures that are used to establish addressability later.

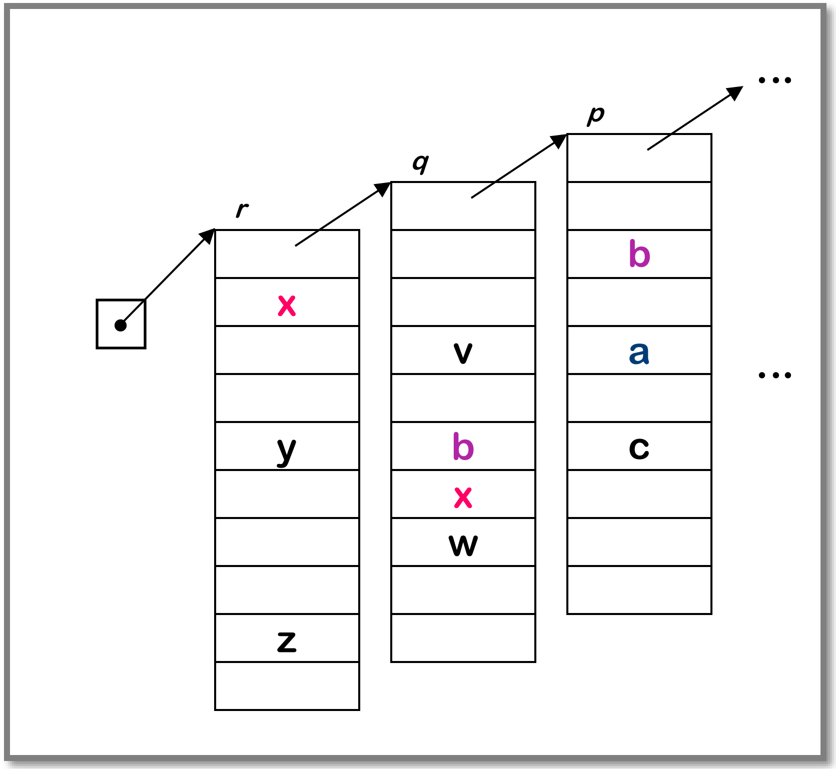
Example

```
procedure p {
    int a, b, c
    procedure q {
        int v, b, x, w
        procedure  r {
            int x, y, z
            ….
        }
        procedure s {
            int x, a, v
            …
        }
        … r … s
    }
    … q …
}
```

```
B0: {
        int a, b, c
B1:      {
            int v, b, x, w
B2:          {
                int x, y, z
                ….
            }
B3:          {
                int x, a, v
                …
            }
            … r … s
        }
        … q …
}
```

Lexically-scoped Symbol Tables

High-level idea
- Create a new table for each scope
- Chain them together for lookup



"Sheaf of tables" implementation
- *insert*() may need to create table
- it always inserts at current level
- *lookup*() walks chain of tables & returns first occurrence of name
- *delete*() throws away level *p* table if it is top table in the chain

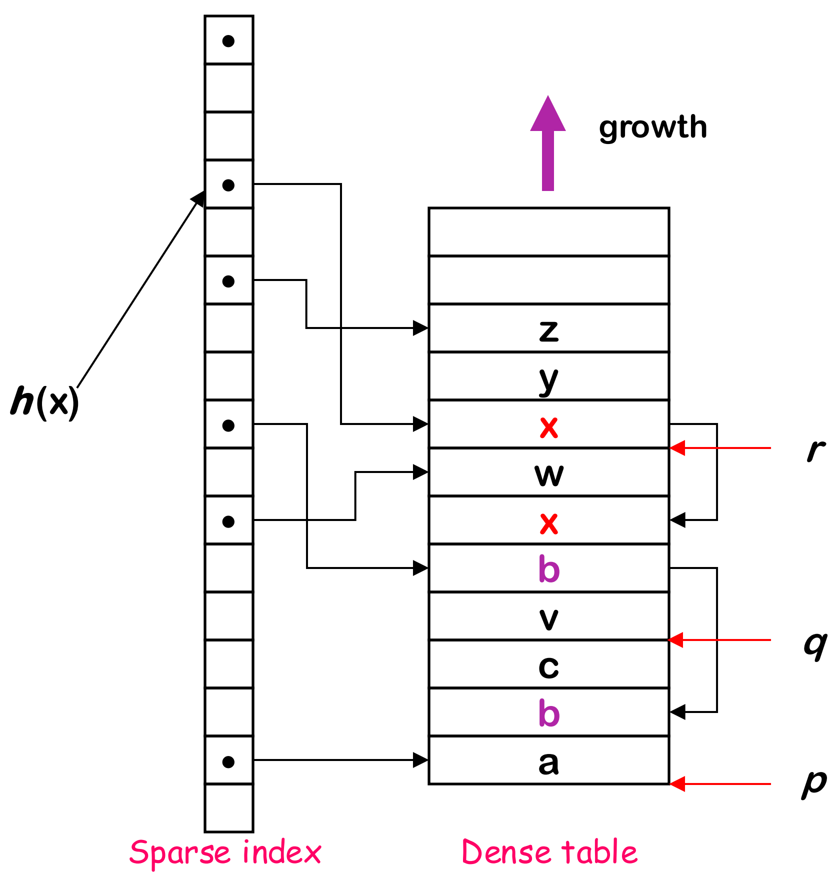
If the compiler must preserve the table (*for, say, the debugger*), this idea is actually practical.

Individual tables are hash tables.

This high-level idea can be implemented as shown, or it can be implemented in more space-efficient (albeit complex) ways.

Implementing Lexically Scoped Symbol Tables

Threaded stack organization



Implementation

- *insert*() puts new entry at the head of the list for the name
- *lookup*() goes direct to location
- *delete*() processes each element in level being deleted to remove from head of list
- use sparse index for speed
- use dense table to limit space

Advantage

- lookup is fast

Disadvantage

- delete takes time proportional to number of declared variables in level

Parser (or treewalk) encounters names by scope, so each scope forms a block at stack top.

The Procedure as an External Interface

Naming plays a critical role in our ability to use procedure calls as a general interface

OS needs a way to start the program's execution

- Programmer needs a way to indicate where it begins
  - The procedure "main" in most languages
- When user invokes "grep" at a command line
  - OS finds the executable
  - OS creates a process and arranges for it to run "grep"
    - → Conceptually, it does a fork() and an exec() of the executable "grep"
  - "grep" is code from the compiler, linked with run-time system
    - → Starts the run-time environment & calls "main"
    - → After main, it shuts down run-time environment & returns
- When "grep" needs system services
  - It makes a system call, such as fopen()

UNIX/Linux specific discussion

Where Do All These Variables Go?

Automatic & Local

- Keep them in the procedure activation record or in a register
- Automatic ⇒ lifetime matches procedure's lifetime

Static

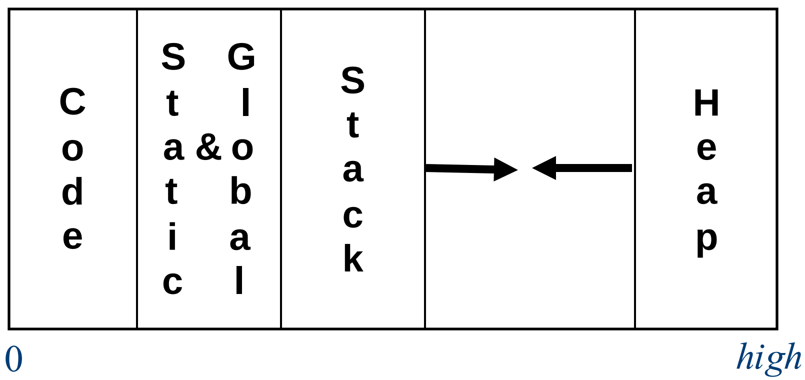
- Procedure scope ⇒ storage area affixed with procedure name
  - &_p.x
- File scope ⇒ storage area affixed with file name
- Lifetime is entire execution

Global

- One or more named global data areas
- One per variable, or per file, or per program, …
- Lifetime is entire execution

Placing Run-time Data Structures

Classic Organization



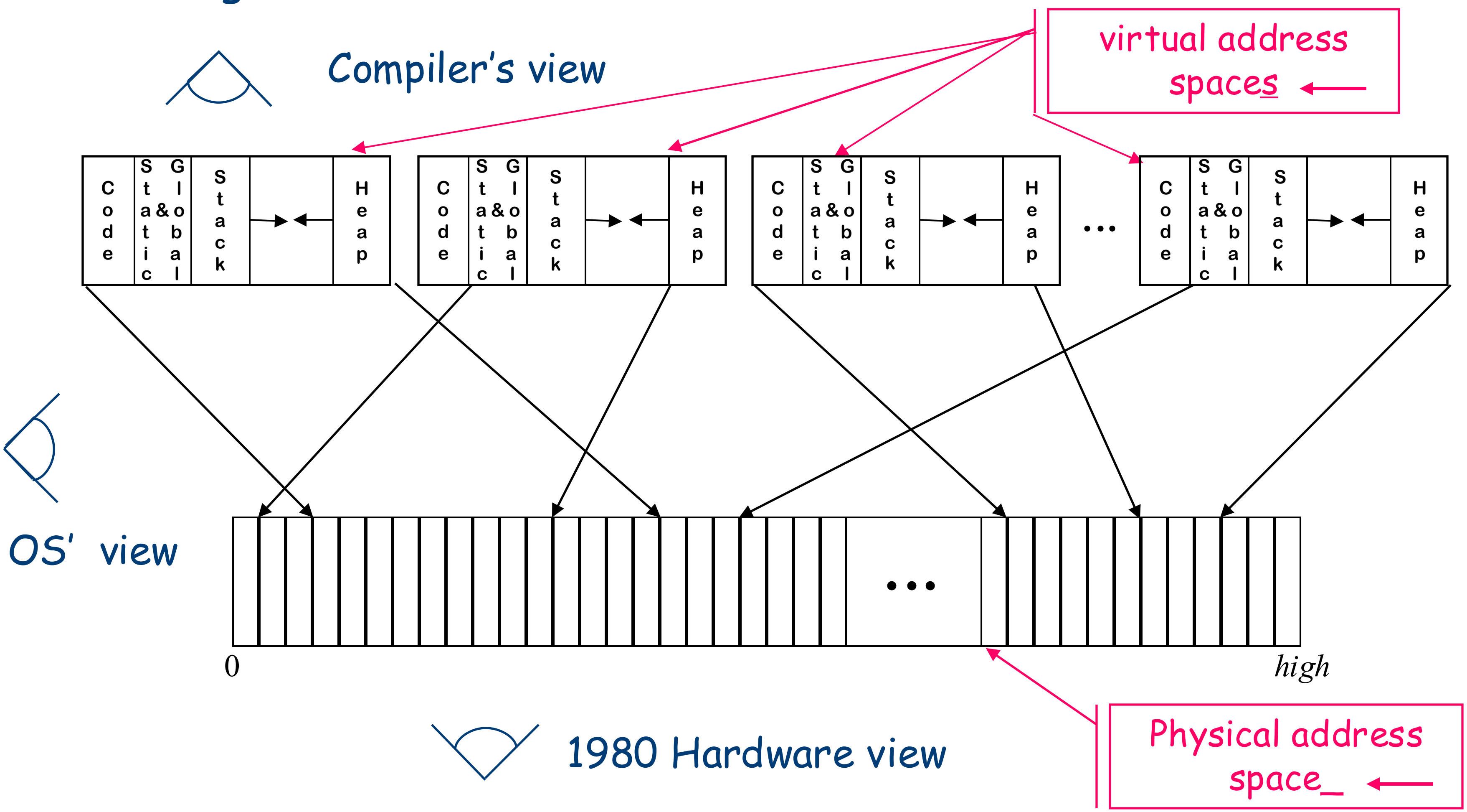
Single Logical Address Space

- Better utilization if stack & heap grow toward each other
- Very old result (Knuth)
- Code & data separate or interleaved
- Uses address space, not allocated memory

- Code, static, & global data have known size
  – Use symbolic labels in the code
- Heap & stack both grow & shrink over time
- This is a *virtual* address space

How Does This Really Work?

The Big Picture

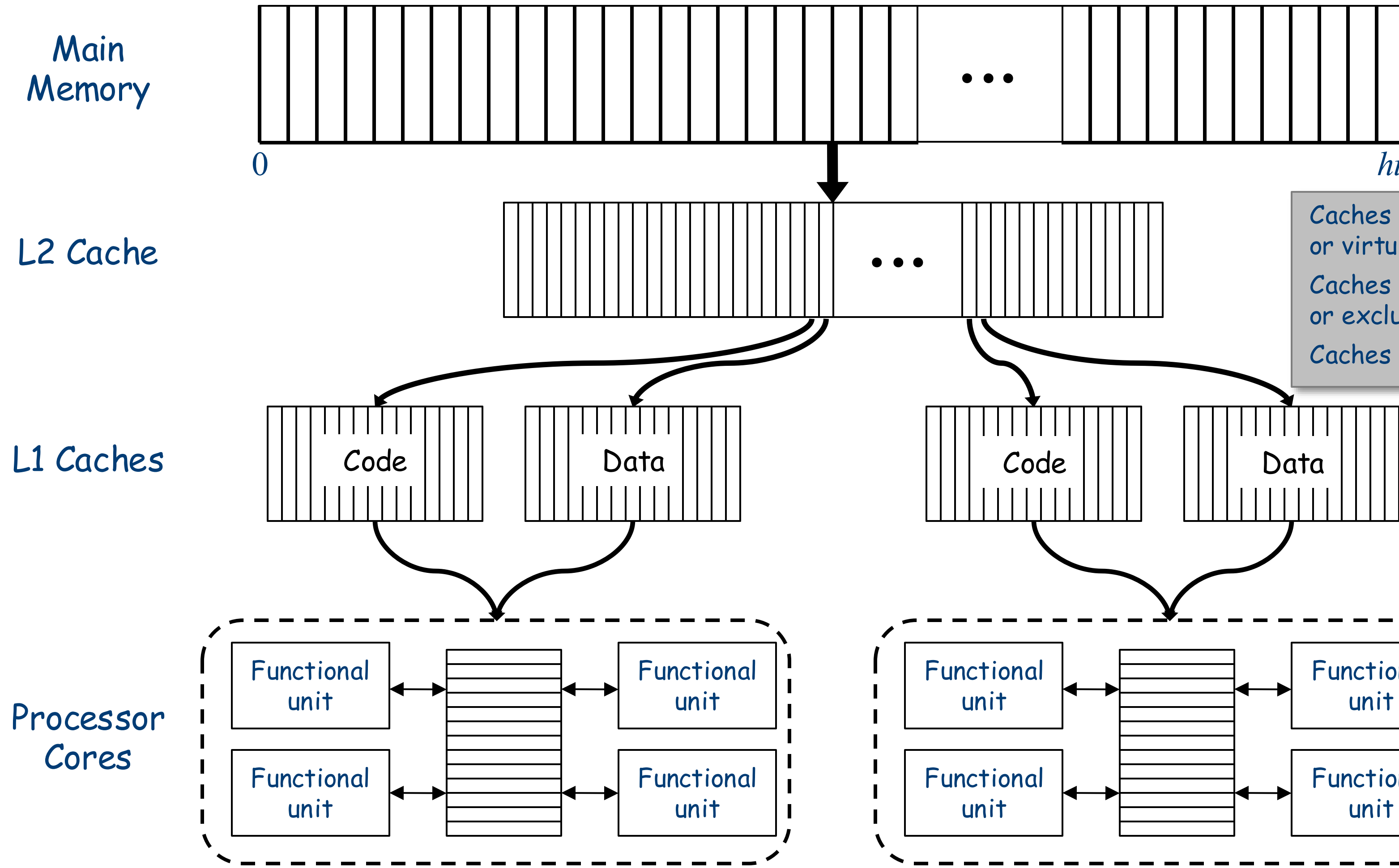


On many modern processors, L1 cache uses physical addresses
Higher level caches typically use virtual addresses

How Does This Really Work?

Most systems now include L3 caches. L4 is on its way.

Of course, the "Hardware view" is no longer that simple



Caches can use physical or virtual addresses

Caches can be inclusive or exclusive

Caches can be shared

Cache structure matters for performance, not correctness

Where Do Local Variables Live?

A Simplistic model

- Allocate a data area for each distinct scope
- One data area per "sheaf" in scoped table

What about recursion?

- Need a data area per invocation (or activation) of a scope
- We call this the scope's activation record
- The compiler can also store control information there!

More complex scheme

- One activation record (AR) per procedure instance
- All the procedure's scopes share a single AR *(may share space)*
- Static relationship between scopes in single procedure

Used this way, "static" means knowable at *compile time* (and, therefore, fixed).

Translating Local Names

How does the compiler represent a specific instance of *x* ?

- Name is translated into a *static coordinate*
  - ‹*level,offset*› pair
  - "*level*" is lexical nesting level of the procedure
  - "*offset*" is *unique* within that scope
- Subsequent code will use the static coordinate to generate addresses and references
- "*level*" is a function of the table in which *x* is found
  - Stored in the entry for each *x*
- "*offset*" must be assigned and stored in the symbol table
  - Assigned at *compile time*
  - Known at *compile time*
  - Used to generate code that *executes* at *run-time*

Storage for Blocks within a Single Procedure

```
B0:  {
         int a, b, c
B1:      {
             int v, b, x, w
B2:          {
                 int x, y, z
                 …
             }
B3:          {
                 int x, a, v
                 …
             }
             …
         }
         …
     }
```

Fixed length data can always be at a constant offset from the beginning of a procedure

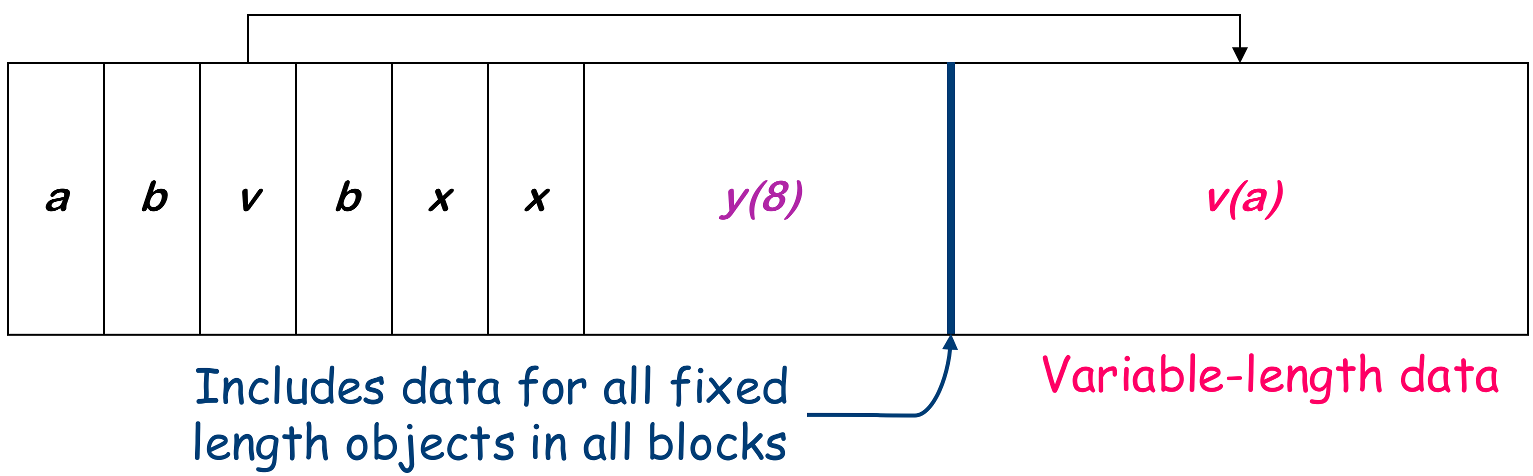
- In our example, the a declared at level 0 will always be the first data element, stored at byte 0 in the fixed-length data area
- The x declared at level 1 will always be the sixth data item, stored at byte 20 in the fixed data area
- The x declared at level 2 will always be the eighth data item, stored at byte 28 in the fixed data area
- But what about the a declared in the second block at level 2?

Variable-length Data

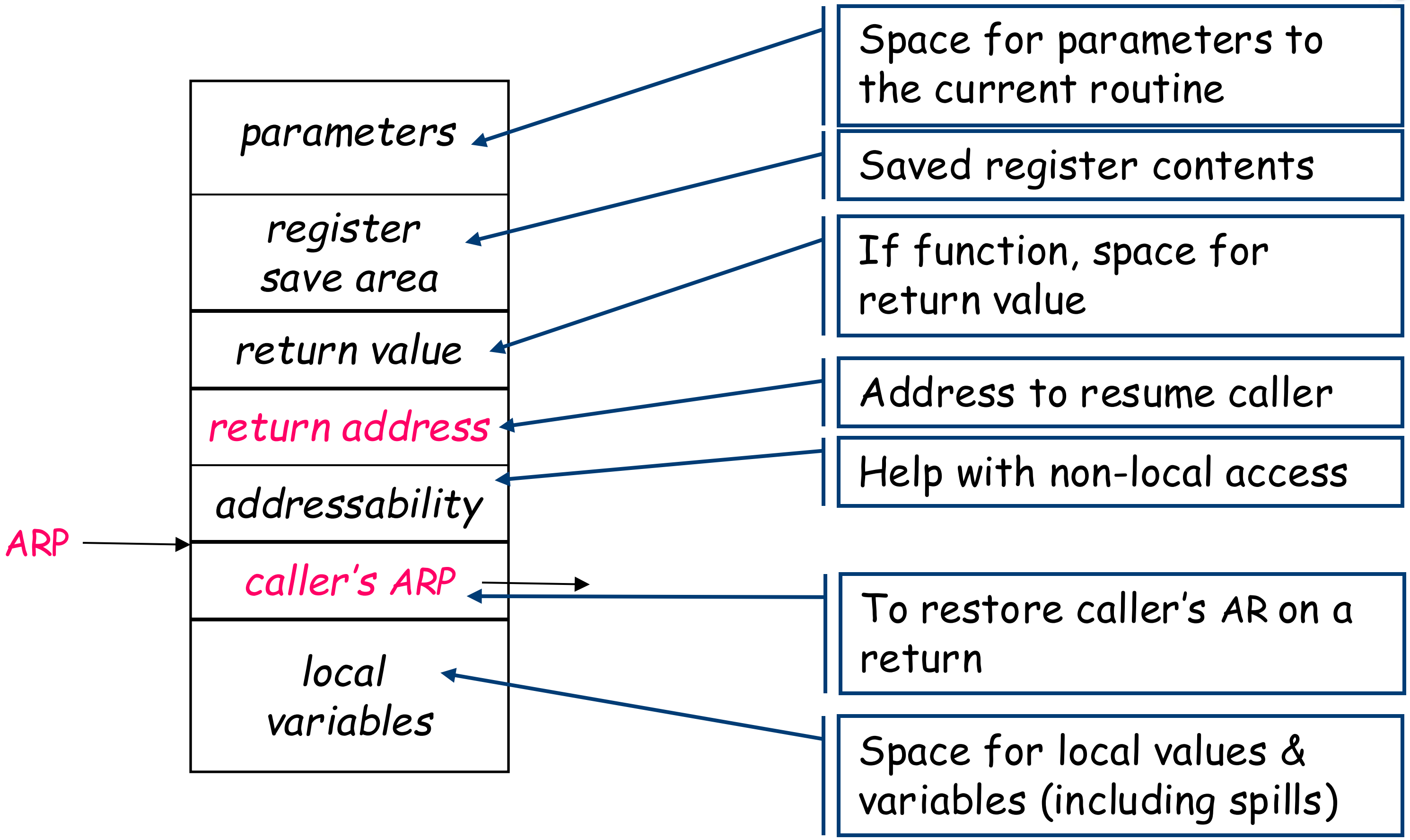
```
B0: { int a, b
        …
        assign value to a
        …
B1:     {  int v(a), b, x
           …
B2:        {  int x, y(8)
              …
           }
        }
    }
```

Arrays

- → If size is fixed at compile time, store in fixed-length data area
- → If size is variable, store descriptor in fixed length area, with pointer to variable length area
- → Variable-length data area is assigned at the end of the fixed length area for the block in which it is allocated (including all contained blocks)



Activation Record Basics



One AR for each invocation of a procedure

ARP ≈ Activation Record Pointer

Activation Record Details

How does the compiler find the variables?

- They are at known offsets from the AR pointer
- The static coordinate leads to a "loadAI" operation
  - Level specifies an ARP, offset is the constant

Variable-length data

- If AR can be extended, put it above local variables
- Leave a pointer at a known offset from ARP
- Otherwise, put variable-length data on the heap

Initializing local variables

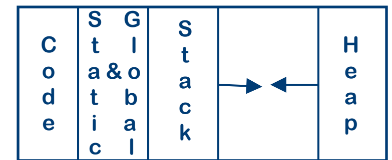
- Must generate explicit code to store the values
- Among the procedure's first actions

Activation Record Details

Where do activation records live?

- If lifetime of AR matches lifetime of invocation, *AND*
- If code normally executes a "return"

⇒ Keep ARs on a <u>stack</u>



Yes! That stack

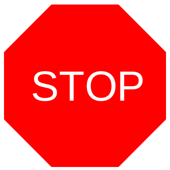
- If a procedure can outlive its caller, *OR*
- If it can return an object that can reference its execution state

⇒ ARs <u>must</u> be kept in the heap

- If a procedure makes no calls

⇒ AR can be allocated statically

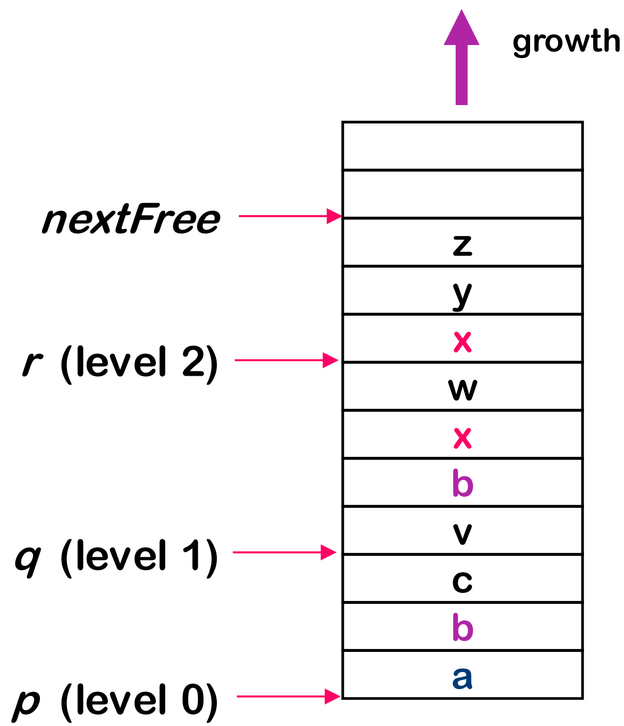
Efficiency prefers static, stack, then heap



Unused Slides

Implementing Lexically Scoped Symbol Tables

Stack organization



Implementation

- *insert*() creates new level pointer if needed and inserts at nextFree
- *lookup*() searches linearly from nextFree–1 forward
- *delete*() sets nextFree to the equal the start location of the level deleted.

Advantage

- Uses <u>much</u> less space

Disadvantage

- Lookups can be expensive