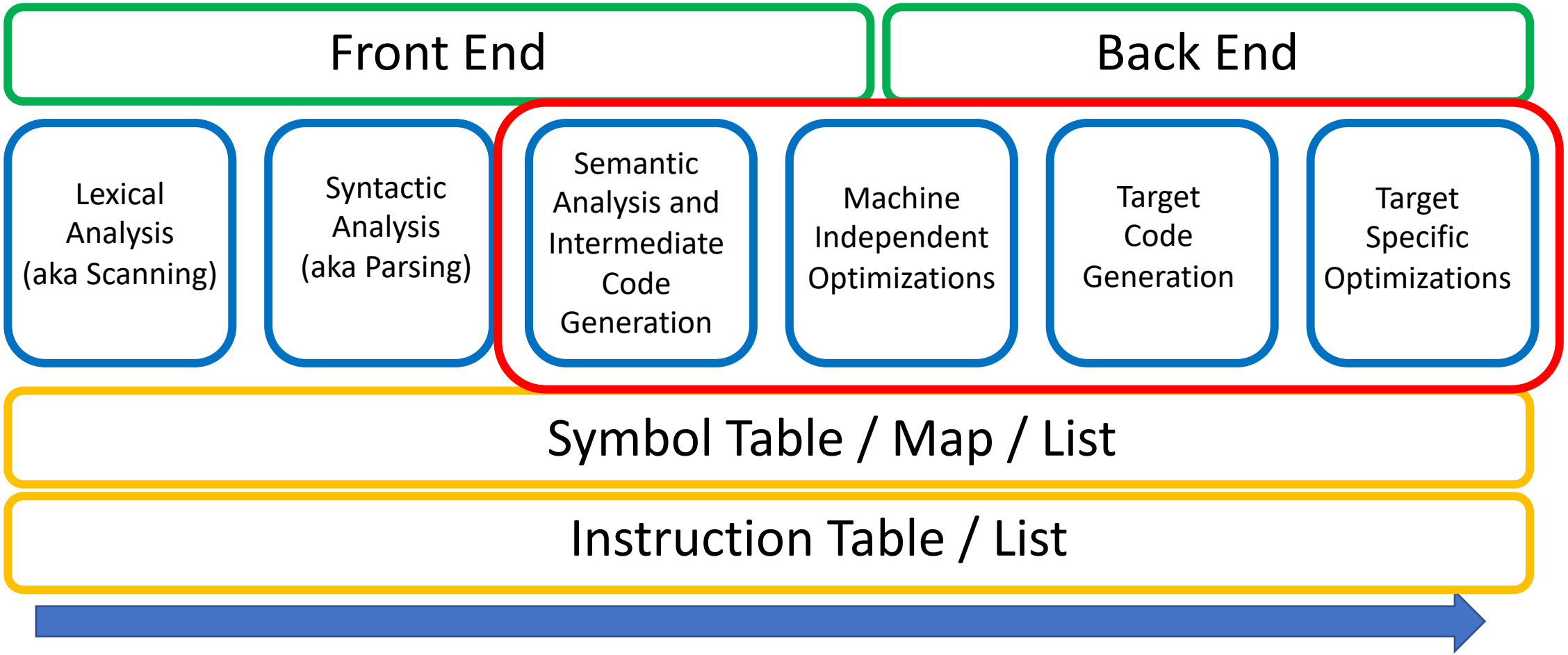
The Environment: Names, Scopes and Bindings

Overview

- Binding time
- Object lifetime and Storage Management
  - Program's stack: static memory allocation
  - Program's heap: dynamic memory allocation
- Scope rules:
  - ”what variable (memory location) am I using in location X?”
  - Reach of a declaration
  - Visibility of variables, functions, objects, methods, etc.

Compilation Overview



Input (*.c file)

Output
(for instance, a binary file)

The Need for Abstractions

- Abstraction:
  - brings something to a higher-level (Compare assembly code against Java code)
  - Hides irrelevant details
  - Focuses on main properties
- Names / symbolic identifiers: addresses and computations
- Subroutines:
  - control abstractions
  - Jump from one point in the program to another one
  - Records / remembers previous state
  - Defines how to pass arguments
  - Defines how to return results

The Need for Abstractions

- Classes (in the Object-Oriented sense):
  - Data abstractions
  - Group data and computations together
  - Abstract “security”

Binding Time

- Binding: association between two things
- Example:
  - name and a storage location
  - name and implementation of a subroutine
- Binding time: the time at which a binding is made
- Several binding times:
  - Language design time: control-flow constructs, data types
  - Language implementation time: some aspects left as “implementation specific”, e.g. the number of bits used in floating point precision
  - Program writing time
  - Compile time: mapping of PL constructs to machine code and memory layout
  - Link time: functions in separate compilation units
  - Load time: when the program is loaded by the operating system; logical to physical address translation
  - Run time: a function activation, dynamic memory allocation

Binding Time

- Also: static vs dynamic
- Umbrella term for several binding times in previous slide
- Compiler-based language implementations tend to be more efficient:
  - Decide layout / location for variables
  - Generates more efficient code
  - Particularly useful in loop-based coded (hotspots in programs)
  - Some decisions are ”local best”: addresses of variables
- Interpreted languages:
  - Decisions and optimization are time constrained
  - Vital information might not be available yet at compile time
  - Most scripting languages delay type-checking to runtime

Object Lifetime

Key events:

- Creation and destruction of objects
- Creation and destruction of bindings
- Deactivation and reactivation of bindings that may be temporarily unusable
- Reference to variables, subroutines

Lifetime

- Binding lifetime: time between creation and destruction of name-to-object binding
- Object lifetime: time between creation and destruction of an object

```
int a;
while (a < 10)
{
  int i;
  …
  if ( a % 2 == 0) {
    int i;
    …
  }
}
```

Lifetime

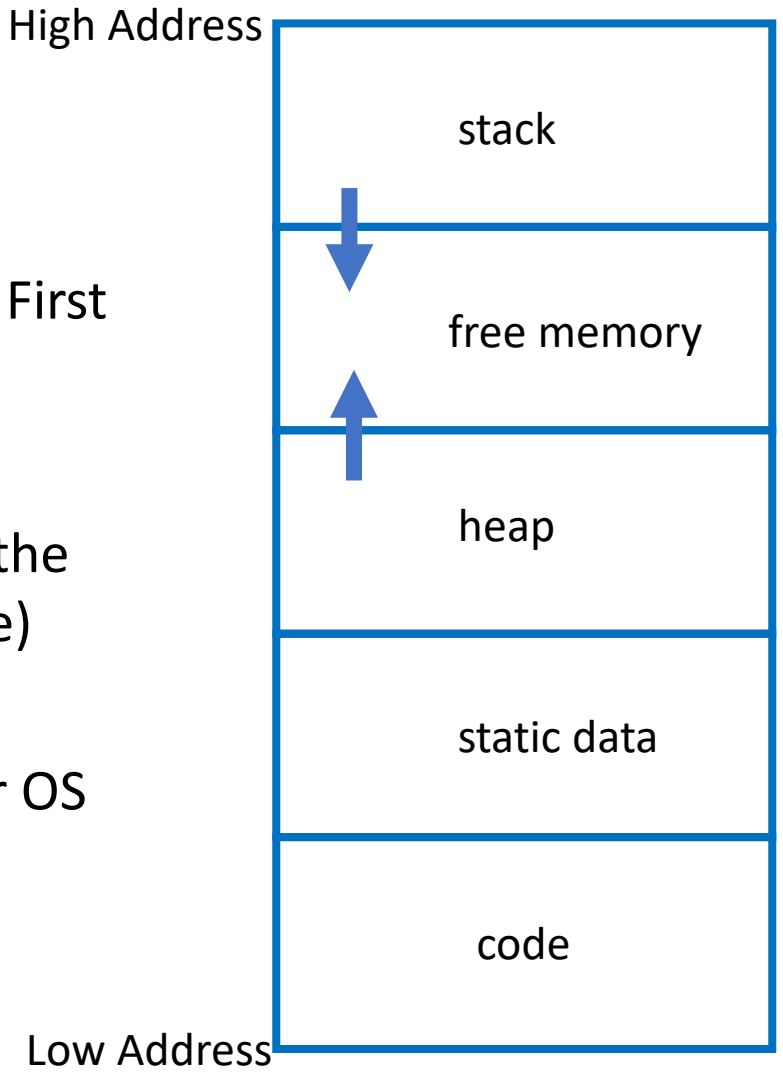
- Binding and object lifetime do not necessarily coincide
- Object may retain value and access potential even without name (binding):
  - Pass by reference & in C++: lifetime of binding shorter than lifetime of object
- Also possible to have a binding lifetime longer than an object lifetime (likely sign of bug):
  - Dangling reference: a pointer without memory associated to it (or memory freed)

Object Lifetimes

- Static: objects with absolute address throughout the program execution
- Stack: objects are allocated and deallocated in LIFO order (Last In, First Out)
  - Example: regular and recursive function calls
- Heap: may be allocated and deallocated at arbitrary times during the program execution; require more general and expensive (timewise) storage management

Note: You probably have heard of these 3 memory segments in your OS or Computer Architecture / Organization class

You can also find this interesting.



Static Allocation

Several examples:

- Global variables
- Program instructions
- Variables that retain value, but associated to single subroutine (e.g. C static variables)
- Numeric and string constant literal, e.g. 10, 10.0 and “10”
- Compiler tables and data structures used in debugging, garbage collection, exception handling

Stack Allocation

- Local variables (to subroutines) are created when the subroutine is called and destroyed when it ends
- Each subroutine call creates a new, separate instance of each local variable
- However, not all languages do (or used to do) this by design:
  - Fortran did not originally support recursion (direct or indirect)
  - Added in Fortran 90
  - Implication 1: could not have 2 or more active calls to the same subroutine
  - Implication 2: essentially no distinction between global and stack variables, but subroutines still called in LIFO order

Stack Allocation

- Interesting piece of info in book (page 119):
  - Design decision influenced by cost of manipulating stack in IBM 704 (introduced in 1954)
  - Programmers had to wait ca. to 30 years for recursive subroutine support
- Compile time constants defined in subroutines can be statically stored:

```
int f () {
   const char * mystr = “error message”;
   // will never change
   …
}
```

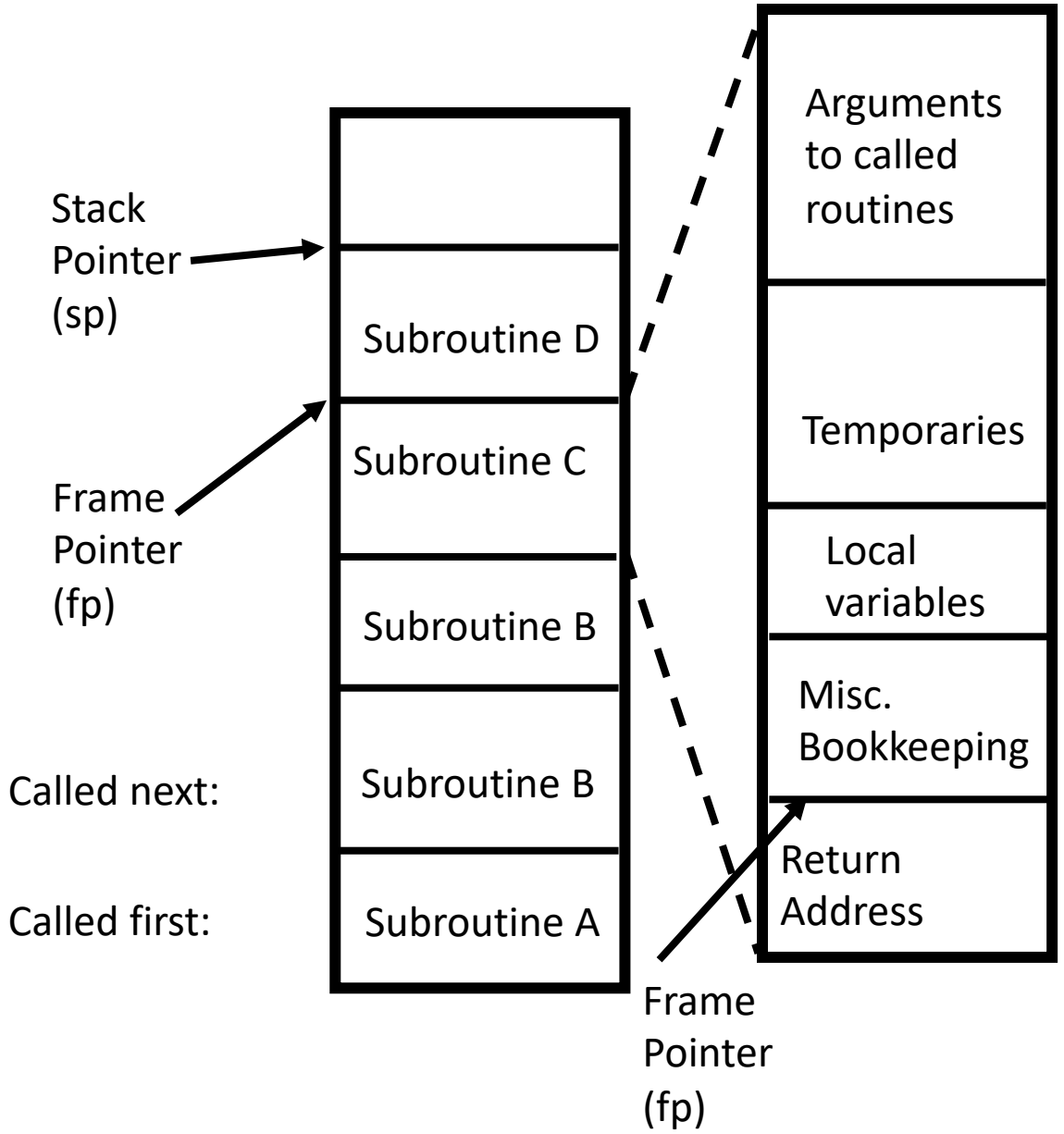
Stack Allocation

- In some cases, compilers can allocate memory for a single instance of a constant, and allow all the calls of a subroutine to use it.
- In other languages (e.g., C and Ada) the compiler initializes the constant at runtime, as it could depend on other variables:
  - Constants then allocated on stack
  - C# distinguishes between compile-time and elaboration-time constants with the keywords const and read-only, respectively.
- Elaboration time = initialization time (during program execution)

```
void f (int a) {
  const int b = 3;
  const int c = a + 1;
  printf (“%d %d %d”, a, b, c);
  if (a > 0)
    f (a – 1);
}
```

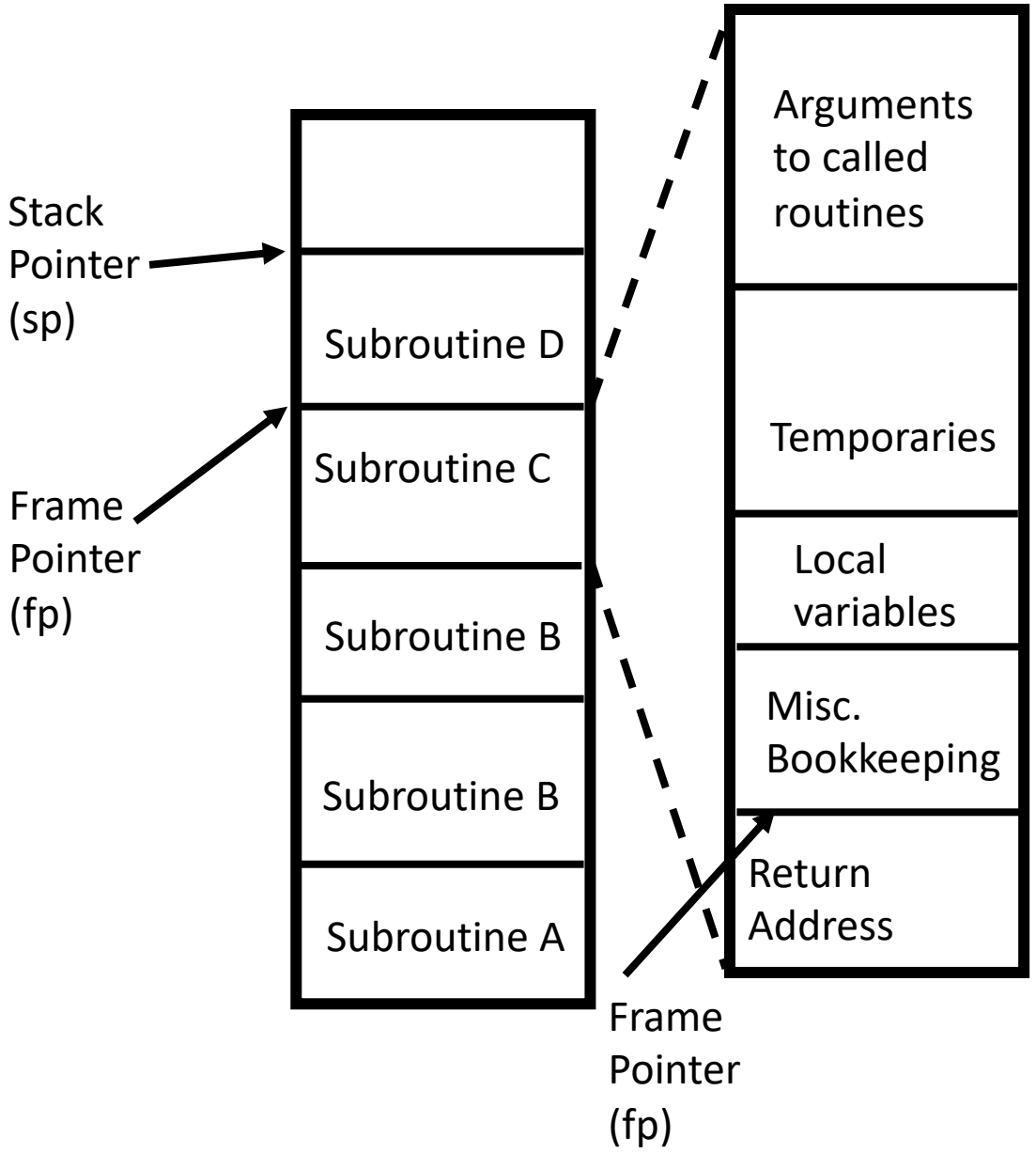
Stack-based Allocation

- Recursion complicates static allocation of variables
- Number of instances of a variable (e.g., a variable named “count” in a function “sum”) is, in theory, unbounded
- Natural nesting of functions allows to allocate memory on the stack
- Each instance (call) of a subroutine assigns memory from the stack for the various variables and constants used in the subroutine



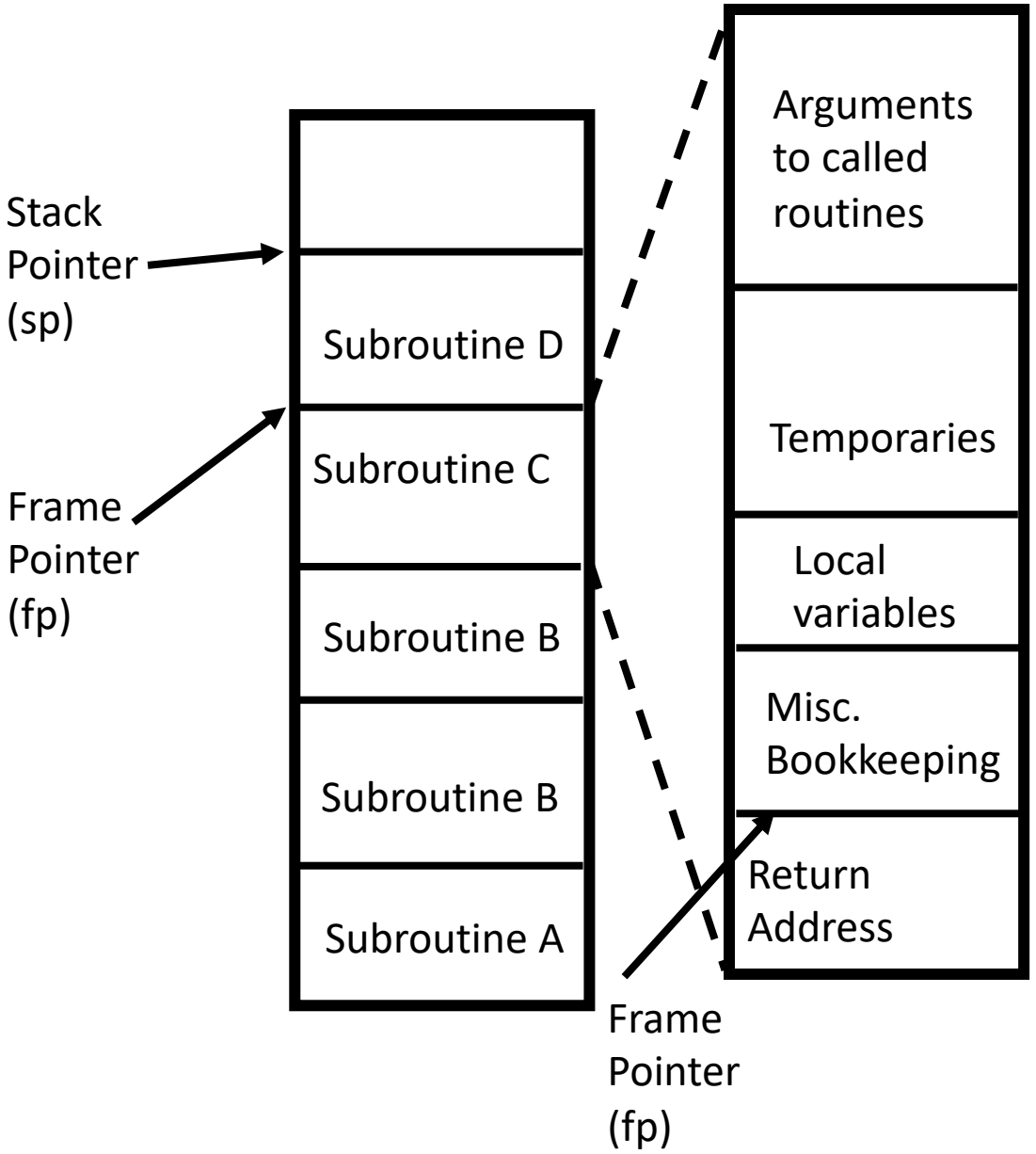
Stack-based Allocation

- Memory of subroutine allocated in a *frame* or *activation record*
- Frame also allocated memory for temporary variables (produced by compiler)
- Bookkeeping information includes: return address, reference to frame of caller (dynamic link), saved values of registers needed by caller and callee (e.g., the program counter)



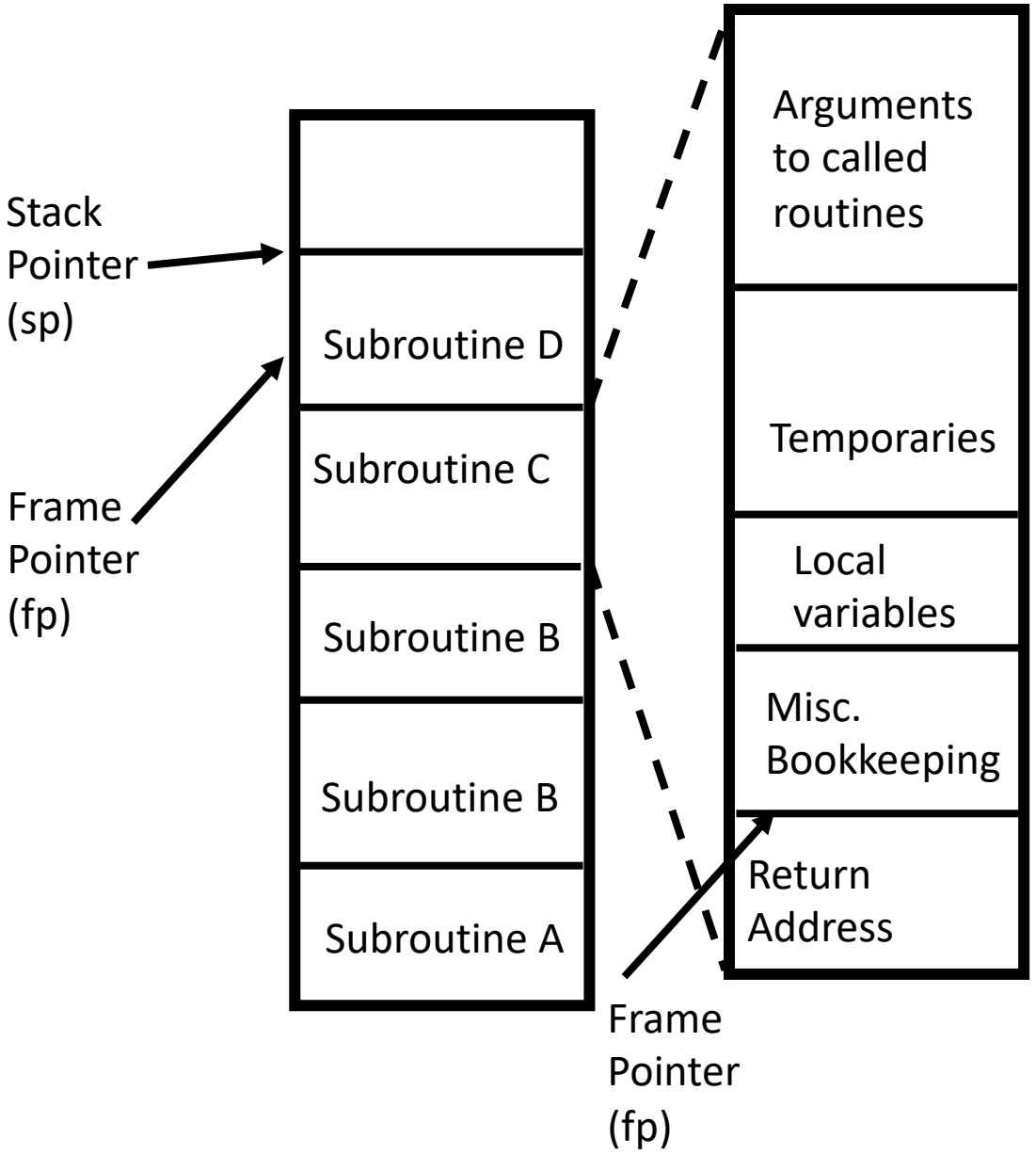
Stack-based Allocation

- Arguments passed to subroutines lie at the top of the frame (it's much more convenient)
- Subroutine actual arguments usually *pushed into the stack*
- Memory layout is heavily implementation and language dependent (Fortran and C assume very different layouts)
- Stack maintenance is mostly responsibility of the caller, before and after calling sequence
- Two parts: prologue and epilogue



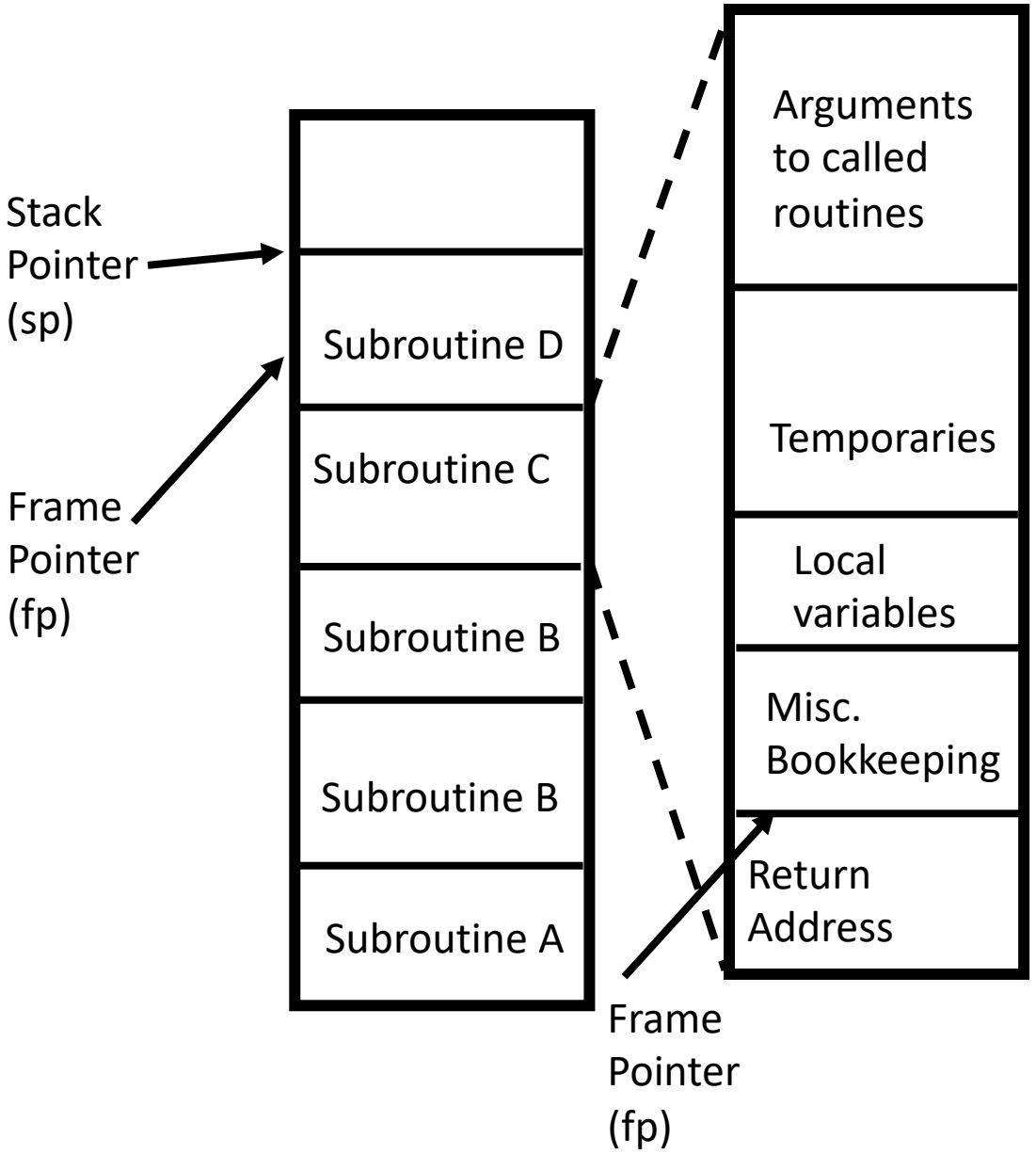
Stack-based Allocation

- Location (actual address) of stack frame not determinable at compile-time, but offsets within frame are
- Frame pointer (fp) points to known location within the new activation frame; useful for external access such as copying results
  - Example: Suppose in subroutine C (see figure) we have a variable “count” with offset 10, then ”count” can be accessed as: fp + 10
- Other addresses accessed by known offsets w.r.t. fp
- PC (Program Counter): frame field storing address of current instruction
- FP, SP, PC usually correspond to machine registers



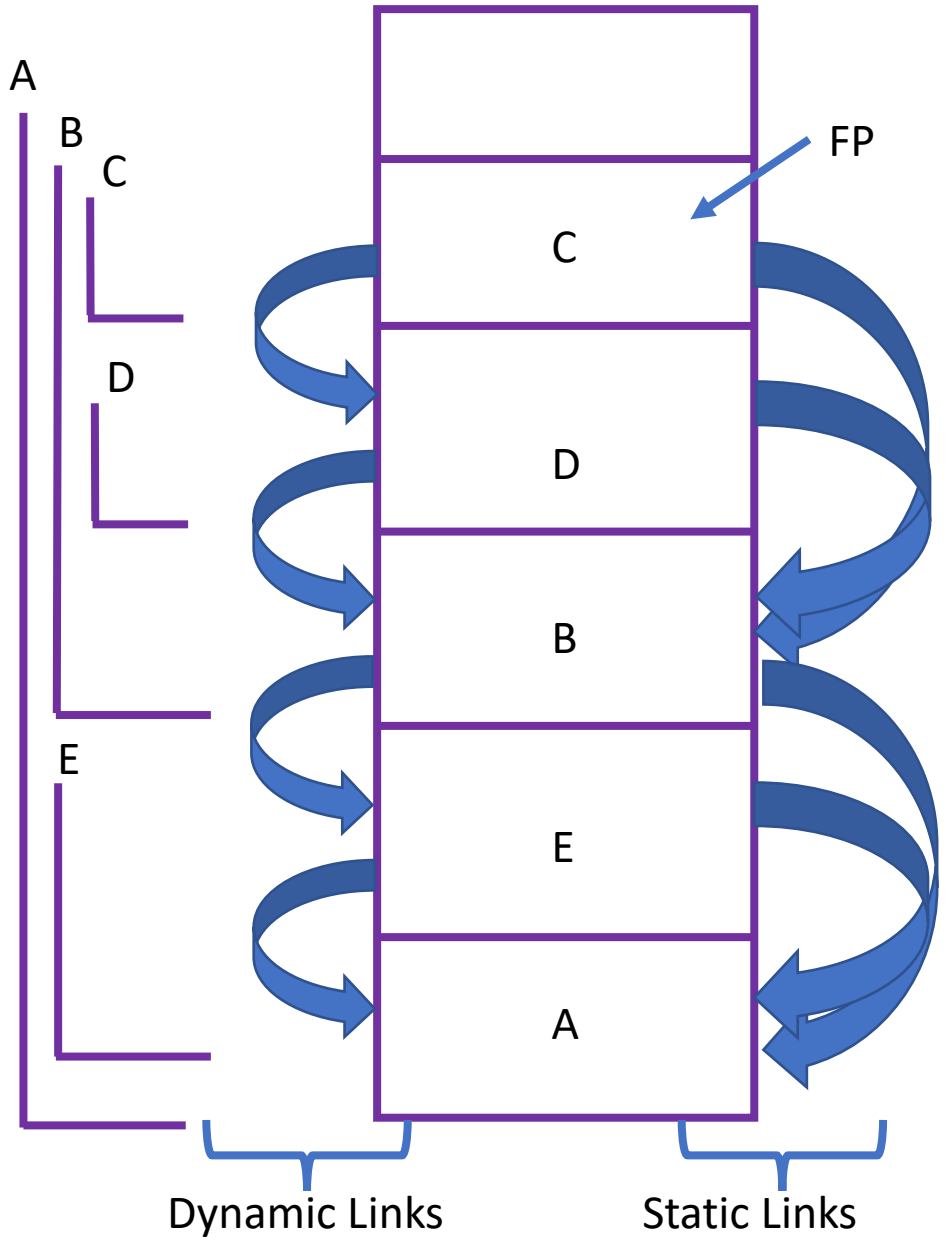
Stack-based Allocation

- Offset of variables (w.r.t fp) can be used in *load* and *store* instruction variants
- Offsets computed statically by compiler with datatype information (e.g. a char is 1 byte, int usually 4 bytes, double usually 8 bytes, struct sum of fields)
- Stack grows downward, towards lower addresses in most language implementations
- Machine instruction sets usually will provide *push* and *pop* instructions for frame manipulation



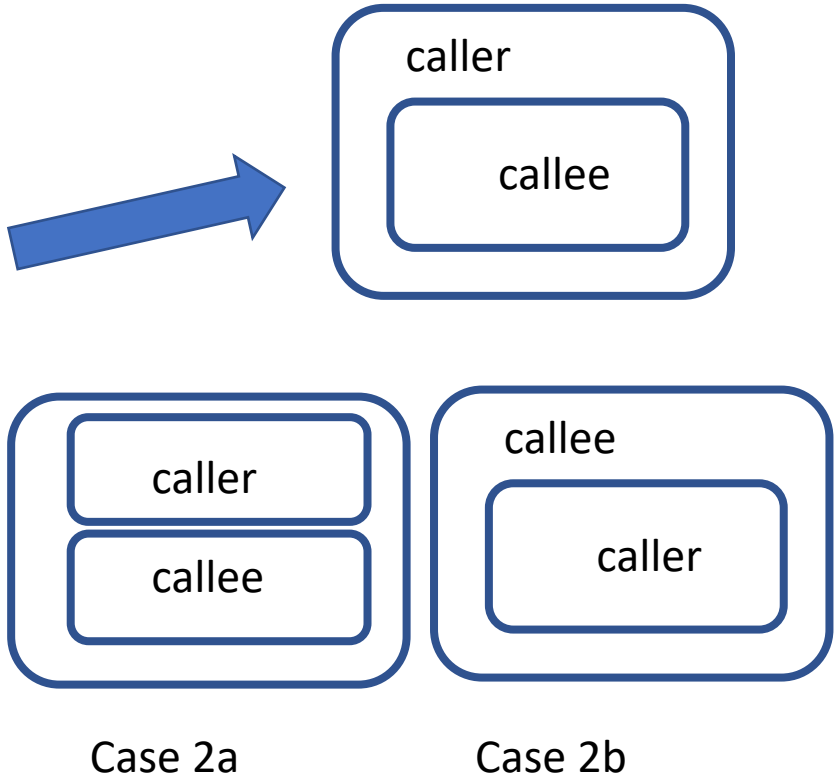
Stack-based Allocation

- Static Link: pointer to the stack frame of the lexically surrounding subroutine
- Dynamic link: pointer to the stack frame making the call to the current subroutine
- Static and dynamic links need not be the same
- Surrounding subroutine will always be active (it needs to be), hence always visible to the callee
- In Figure: all five subroutines are visible from B, C and D; A and E can see themselves and B (but can't see C nor D)
- In the example (Figure), D is called from B, but can't be called from A nor E, as B must be active



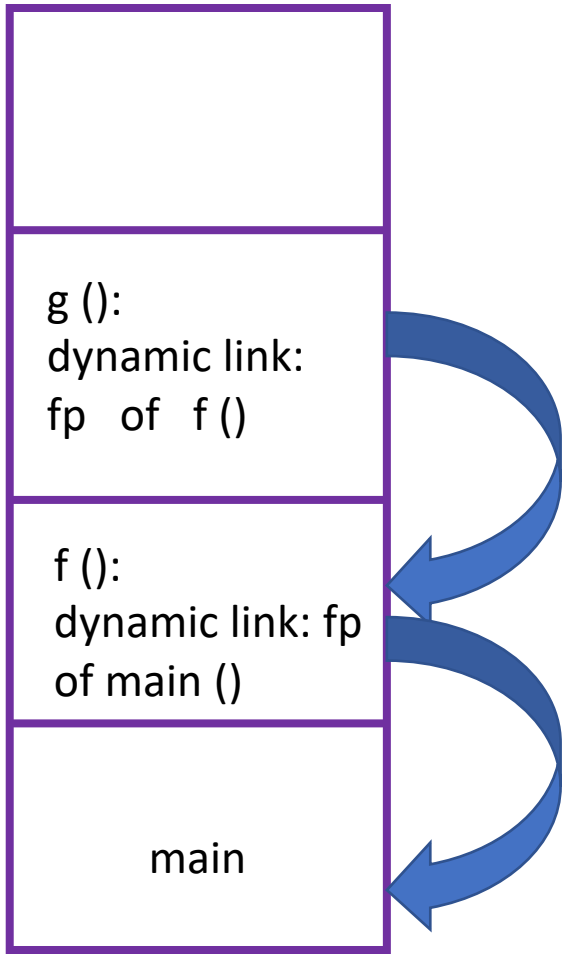
Maintaining the Static Link

- Need some additional work in languages with nested subroutines
- Most work falls in the caller side
- Work depends in the nesting of the callee:
  - Callee nested inside caller: caller passes itself as the static link of the callee
  - Callee is k >= 0 scopes outward of caller:
    - Scopes surrounding callee also surround caller
    - Caller dereferences its own static link k times and passes the result as the static link of the callee



Dynamic Link Example

```
void f(int & z) {
  int f_a = 2;
  z = 3;
  g(f_a, z);
}
void g(int & a, int & z) {
  int g_b;
  g_b = z + a;
}
main (){
  int main_z = 1;
  f(main_z);
}
```



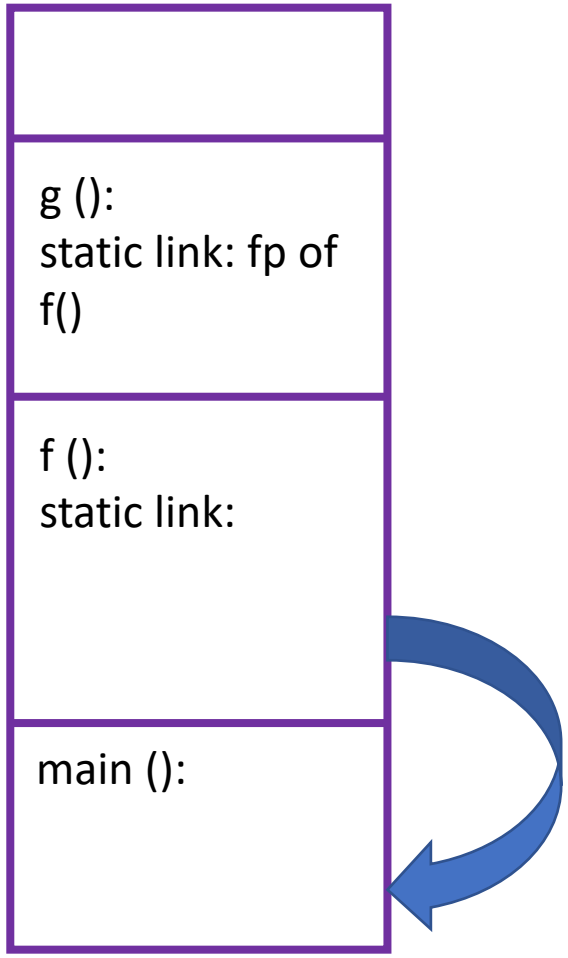
To access main_z / z in f:
- Follow dynamic link to main
- Dynamic link gives fp (frame pointer)
- address(z) = offset(z) + fp(main)

To access z in g:
- Follow dynamic link to f, then from f to main
- address(z) = offset(z) + fp(main)

To access a in g:
- Follow dynamic link to f
- address(a) = offset(a) + fp(f)

Static Link Example: Callee nested in Caller

```
void f() {
  int f_a = 1;
  void g() {
    int g_;
    g_b = f_a + 2;
  }
  g();
}
main () {
  f();
}
```



At run-time:

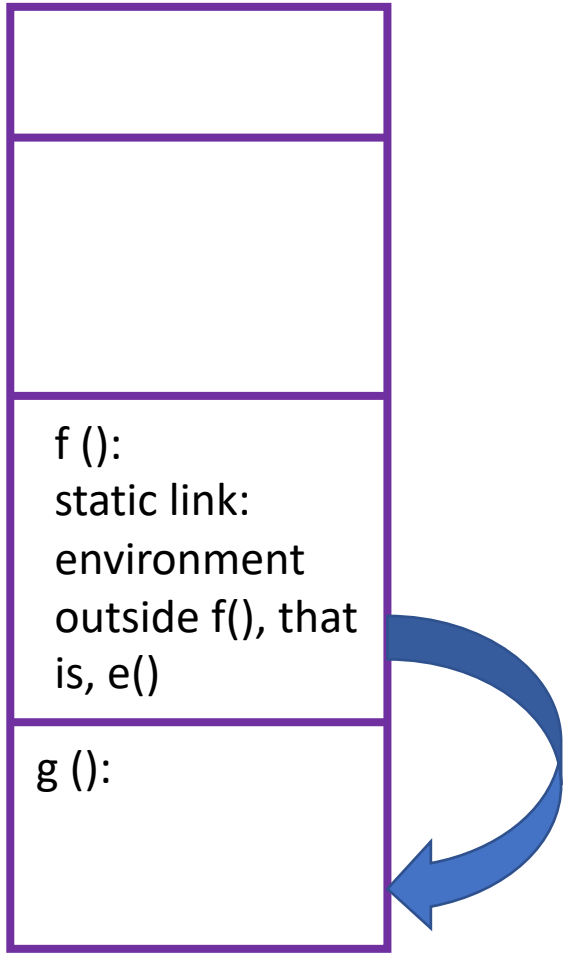
- main() calls f()
- f() calls g()
- g() uses f_a, which is non-local

At compile-time:

- g() realizes f_a is non-local
- g() “climbs up” one level to find the environment where f_a is declared, i.e. f()
- Compiler stores the fp of f() as an static link in g()
- address(f_a) = offset(f_a) + fp(f)

Static Link Example: Caller nested in Callee

```
void e() {
  int e_a = 0;
  void f() {
    void h() {
      void g() {
        e_a = 1;
        f();
      }
    }
    e_a = 2;
  }
}
```



At run-time:

- g() was already called, for instance with e()::f()::h()::g()
- g() then calls f()

At compile-time:

- g() calls f(), which is declared k=2 levels outside it
- g() "climbs up" to find the first common environment to both itself and f(), that's e()
- g() passes the fp of e() as the static link to f()
- address(e_a) = offset(e_a) + fp(e)
- g() also has static links to h(), f() and e(), and anything else outside e()
- Also note, g() can call f() because "it can see f()"

Typical Calling Sequence

Caller

- Save registers
- Compute values of arguments, move them into stack / registers
- (if language with nested subroutines) Compute static link and pass it as a hidden argument
- Use special instruction to jump to address start of subroutine (includes saving the return address in the stack or in a register)

- Moves returned values to wherever needed
- Restores pending registers

Callee

- Allocates a frame by deducting some constant offset from the sp
- Saves old frame pointer into the stack, update to the newly allocated frame

Prologue

- Move return value (if any) to a register, or specific address given by the caller (possibly in the stack)
- Restores register values from the caller (inc. fp and sp)
- Jumps to return address

Epilogue

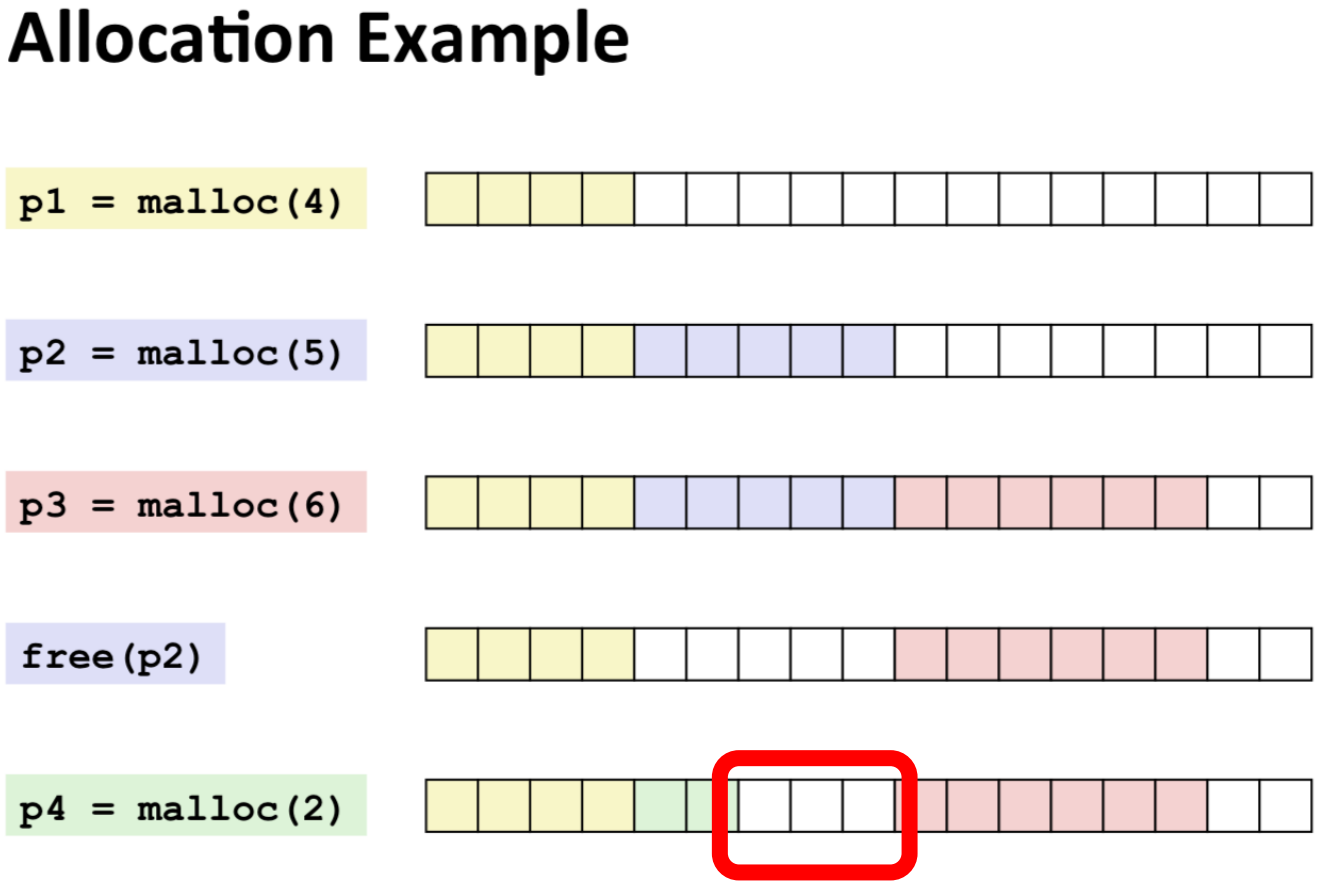
Heap-based Allocation

- Heap: program segment
- Program can use memory from it during its execution
- Require two abstractions: allocation (e.g. new) and deallocation (e.g. free)
- BTW: Dynamic allocation is a performance killer
- Heap management was an active research area: speed and space concerns
- Space: internal (unused within a block) and external fragmentation (used and unused blocks/space scattered and interleaved)

Heap-based Allocation

- Very often, memory blocks kept in a single linked list: the free list
- At program start, free list contains a single node
- Each new memory request assigns slots from the free list → free list changes over time
- Several algorithms (but below just 2):
  - First fit: select the first slot in the free list with sufficient capacity
  - Best fit: traverse the whole free list to find the best match → higher allocation cost
- If chosen block is too large, it's partitioned; unneeded part returned to the free list → leads to memory fragmentation:
  - **Internal**: unused space within allocated memory blocks
  - **External**: disjoint and smaller pieces of available memory
- Options for coalescing (joining adjacent nodes in the free list) when the memory is returned to the *pool* (the heap)

Heap-based Allocation



Heap-based Allocation

- Single free list incurs in linear cost in the number of free blocks
- Alternative: have free lists of various sizes
- Requests rounded up to next standard size
- Sizes can be set statically or dynamically
- Issues with external fragmentation:
  - Degrades performance over time
  - Makes harder to satisfy new memory requests
- Two common mechanisms:
  - Buddy system: powers of 2
  - Fibonacci heaps: slightly lower internal fragmentation (sequence grows slower than powers of 2)
- Compaction eliminates external fragmentation: find and move already allocated blocks

Garbage Collection (GC)

- Allocation and deallocation of objects is explicit in some languages (malloc, new and free operations in C and C++)
- In other languages, objects (broadly speaking) are automatically deallocated by the runtime (aka the environment)
- Garbage collector: part of the runtime in charge of finding and freeing objects that are not used anymore
- Examples of languages with GC: Java, C#
- Arguments in favor of explicit object management: speed and simplicity (shift burden to programmer)
- Arguments in favor of (automatic) GC: avoid programming errors (dangling references, memory leaks)

Scope Rules

- Scope: textual region of program in which binding is active
- In most modern languages, scope is statically (compile-time) determined
- In C, a new scope is introduced when:
  - A subroutine starts
  - Entering a new block ({…})
- Runtime creates new bindings for local objects
- Deactivate previous global and/or non-local binding (w.r.t. to current scope)
- On subroutine exit, destroy local bindings, reactivate global/non-local bindings previously active

Scope Rules

- Binding can be determined statically (but executed at runtime), i.e., we can look at the code of a program and know which binding will be active
- Other languages (APL, Snobol, Tcl and Lisp) were dynamically scoped:
  - Bindings depend on the flow of execution
- Informally, “scope” also refers to specific program region in which something does not change or where something is in effect
- Examples of scope: a block, a module, a class/object, a structured control-flow construct
- Some languages call the binding process *elaboration*
  - May include allocation of objects in stack and assignment of initial values

Scope Rules

- Referencing environment:
  - Set of active bindings at some point of the program's execution
  - Sequence of scopes that can be examined (in order)
- Binding rules:
  - When a reference to a subroutine is chosen
  - Happens when a reference to a subroutine is stored in a variable, passed as a parameter or returned as a function value (e.g. a lambda function)
  - Deep binding: happens when a subroutine is passed as argument
  - Shallow binding: occurs when reference to subroutine is used

```
function f1() {
  var x = 10;
  function f2(fx) {
    var x;
    x = 6;
    fx();
  }
  function f3() {
    print x;
  }
  f2(f3);
}
```

Pseudocode Example

Static Scoping

- With STATIC (LEXICAL) SCOPE RULES, a scope is defined in terms of the physical (lexical) structure of the program
- Basic scheme: Current binding for names found in closest surrounding block (e.g. braces, indentation in python)
  - The determination of scopes can be made by the compiler
  - All bindings for identifiers can be resolved by examining the program
  - Typically, we choose the most recent, active binding made at compile time
  - Most compiled languages, C and Pascal included, employ static scope rules
- Several variants of basic scheme

Static Scoping

- Pre Fortran90:
  - Distinguish between global and local variables
  - Scope of local variables limited to subroutine in which they appear
  - Non-declared variables (yes, non-declared) assumed to be local, and of type integer if the name start with letters I-N, real otherwise
- Conventions for successors changed
- Implicit declarations could be turned off from Fortran90 onwards
- Lifetime of local variable normally limited to single execution of subroutine
- Fortran: programmer can explicitly *save* the value of a variable; similar mechanism to C *static* variables or Algol *own*
  - Lifetime of variable expands program execution
  - Name-to-variable binding inactive when subroutine not in execution

Nested Subroutines

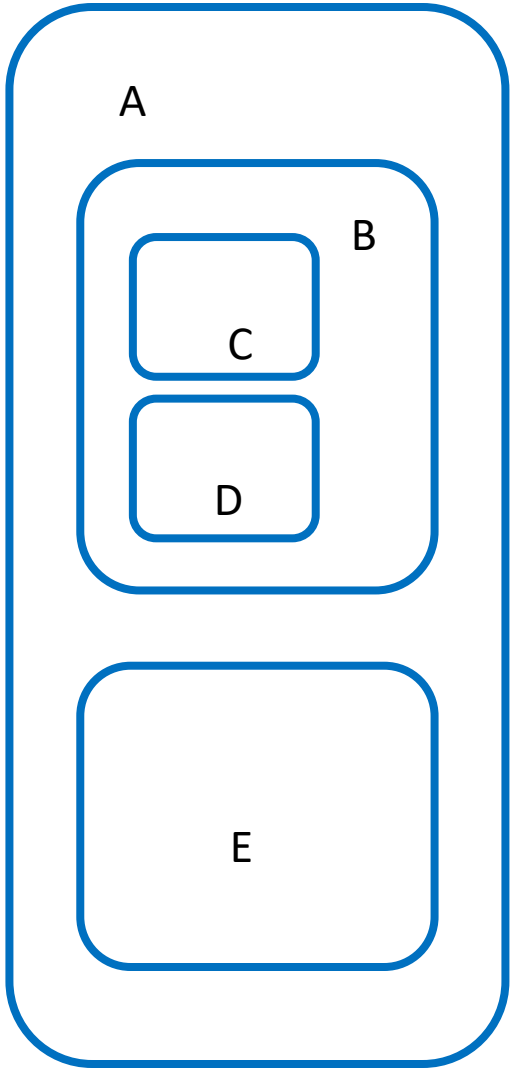
- Ability to define subroutines inside each other
- Introduced in Algol 60
- Feature in several programming languages: Ada, Common Lisp, Python
- Other languages (e.g. C and descendants), allow classes or other scopes to nest
- Algol used ”closest nested rule” for bindings
- When a name is hidden by a nested declaration, two options:
  - Hidden name is completely inaccessible
  - If language permits, add a qualifier such as the routine name

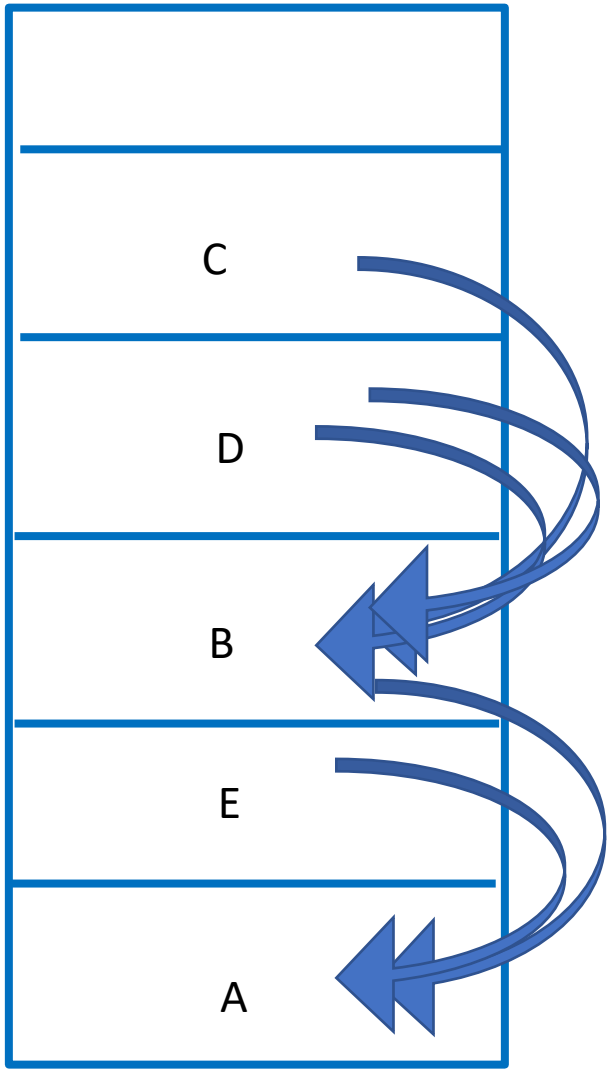
```
function
  E(x: real): real;
  function F(y: real): real;
  begin
    F := x + y
  end;
begin
  E := F(3) + F(4)
end;
```

Pascal Example

Non-local Access

- Frame pointer (fp) gives access to calling context / activation
- How to access variables in other active frames?
- Problem: frames in activation stack can appear in different order from the nested declaration
- Static links: provide access to outer surrounding subroutine
- Compiler generates code to chase static links at runtime





Declaration Order

- Design question: can an expression E refer to any name declared in the current scope, or only to names declared before E in the scope?
- Some languages (e.g. Algol 60, Lisp) required all declarations to be made at the beginning of the scope (the begin/end or {})
- Pascal case:
  - Changed to allow declarations in the middle of blocks
  - However, scope of declaration remained the whole block
  - Produced weird semantic errors (see book, Sec. 3.3.3)
  - Then modified scope rules to affect only from declaration point onwards (like C)
- Special mechanisms to support recursive types and subroutines: forward declaration:

```
class MyClass;

typedef MyClass myclass_t;
```

- Other languages do not require declarations (e.g. python), variables created on first use

Declarations and Definitions

- Names need to be known and available before being used
- Problem arises in recursive types and subroutines
- What if two structures need to reference each other?
- C and C++ distinguish between *declaration* and *definition*
- Declaration: sets name and scope, may skip some details
- Definition: completes object (in the broad sense) description

```
struct node;
struct tree {
  struct tree * parent;
  struct node * first;
};
struct node {
   struct tree * sibling;
};
```

```
int sum1 (int x);
int sum2 (int y) {
  …
  return sum1(y);
}
int sum1 (int z) {
  …
  return sum2(z);
}
```

Dynamic Scoping

- Binding depends on control-flow and order of subroutine invocation
- Rule of thumb: current/applicable binding is the one most recently used (and not yet destroyed)
- Side-effects:
  - Semantic rules of language dynamically enforced
  - Type-checking and arguments checking deferred to runtime
- Languages with dynamic scope tend to be interpreted

Static vs Dynamic Scope Rules

```
program scopes (input, output );
var a : integer;

procedure first;
begin
a := 1;
end;

procedure second;
var a : integer;
begin
  first;
end;

begin
        a := 2; second; write(a);
end.
```

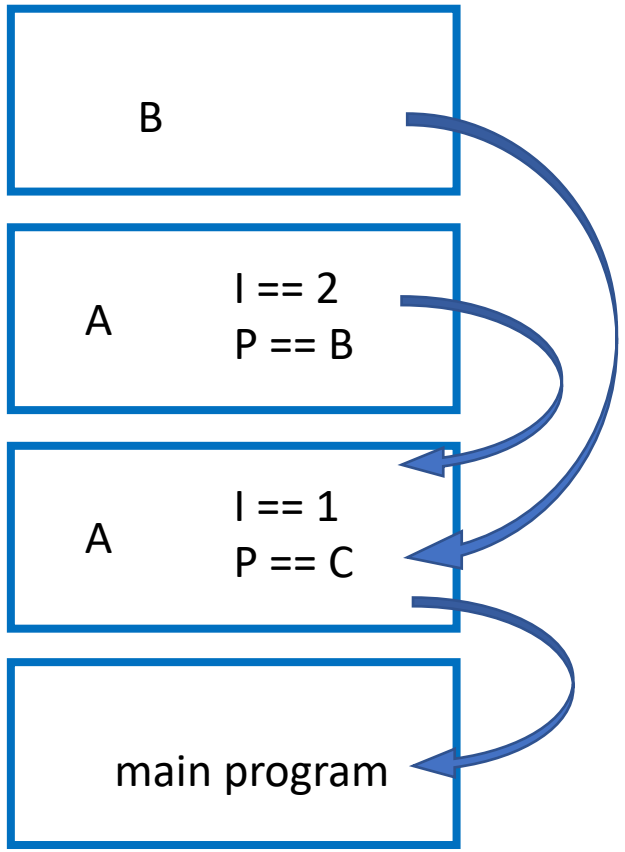
- If static scope rules are in effect (as would be the case in Pascal), the program prints a 1
- If dynamic scope rules are in effect, the program prints a 2
- Why the difference? At issue is whether the assignment to the variable a in **procedure** first changes the variable *a* declared in the main program or the variable a declared in **procedure** second

Static vs Dynamic Scope Rules

```
def A(I,P):
  def B():
    print(I)
  if (I>1):
    P()
  else:
    A(2,B)

def C():
  pass  #do nothing

A(1,C) # main program
```



- First: binding matters when passing functions as parameters is possible
- Python example of static scoping:
  - deep binding: Program prints 1
  - shallow binding: it would print 2

Binding of Referencing Environments

- Referencing environment: collection of scopes that are examined (in order) to find a binding
- SCOPE RULES: determine the scope collection and its order
- BINDING RULES determine which instance of a scope should be used to resolve references when calling a procedure that was passed as a parameter
  - they govern the binding of referencing environments to formal procedures
- Binding time in languages with static scoping and nesting declaration matters because recursive subroutines might have more than one instance
- Closure: captures the current instance of every object at the time the closure is created

Names within Scope

- Names are not necessarily unique
- Name reuse can take several forms: aliases, overloading, polymorphism
- Aliasing:
  - Two or more names that refer to the same object in a program, at the same moment
  - Arises naturally in pointer-based programming languages
  - Pointer aliasing can even disallow later program optimizations
  - C provides language constructs (i.e. restrict) to state that some variables do not alias

```
void stuff (int * a, int * b)
{
  *a += 2;
  *b *= 2;
}
void caller ()
{
  int a = 1;
  stuff (&a, &a);
}
```

```
void stuff (int & a, int * b)
{
  a += 2;
  *b *= 2;
}
void caller ()
{
  int a = 1;
  stuff (a, &a);
}
```

Overloading

Overloading:

- +: boils down to different machine instructions, specific to datatype
- In a compiler, overloading can be resolved by returning a list of matching candidates; then choose based on semantic checks (type, number of arguments, etc)
- In Ada, identifiers **oct** and **dec** can refer to predefined months of a enumerated type or to numeric bases; decide with context
  - Can add a disambiguating qualifier such as: print (month' (oct));
- In C#, every use of an enumeration constant must be prefixed with the type name: pb = print_base.oct

```
void func (int a, int b);
void func (float a, float b);
void func (double * arr);
```

Function overloading in C++

Overloading

- Several languages provide mechanisms to:
  - Change the default behavior of operators
  - Define new operators

- In Haskell:

```
let a @@ b = a * 2 + b
```

Defines a 2-argument, infix operator named @@

Could also have defined it as:

```
let (@@) a b = a * 2 + b
```

In C++:

```
class vector {
  int * data;
  int n;
  …
  vector operator+(vector v1, vector v2) { … }
  vector * (vector src, int s) { … }
};
…
vector w, v, z;
…
 w = v + z;
```

Overloading

- Two other related concepts to overloading: *coercion* and *polymorphism*
- Coercion: automatically converts value of one type into another; type casting is an example
- Polymorphism: allow several implementations of subroutines with the same name to behave differently
  - In C++, same function signature (return type and arguments) behaving differently in a hierarchy class

Overloading

```
void func (int a, int b);
void func (float a, float b);
void func (double * arr);
```

```
int func (int a, int b) {
  return a + b + 1;
}
float func (float a, float b) {
  return a + b + 1.5;
}
int main () {
        int x, d = 1;
        float y, z, a,b,c;
        a = 1; b = 2; c = 3;
        x = func (a,b);
        y = func (a,b);
        z = func (d,b);
        printf ("x = %d\n", x);
        printf ("y = %f\n", y);
        printf ("z = %f\n", z);
        return 0;
}
```

```
class employee {
  …
  float salary () { return 100};
};
class manager : public employee {
  …
  float salary () {
     return employee::salary () * 2;
  }
};
class owner : public manager {
  …
  float salary () {
     return manager::salary () * 3;
  }
};
```