The procedure abstraction

Separate compilation

- allow us to build large programs
- keeps compile times reasonable
- requires independent procedures

The linkage convention:

- a social contract
- machine dependent
- division of responsibility

The linkage convention ensures that procedures inherit a valid run-time environment and that they restore one for their parents.

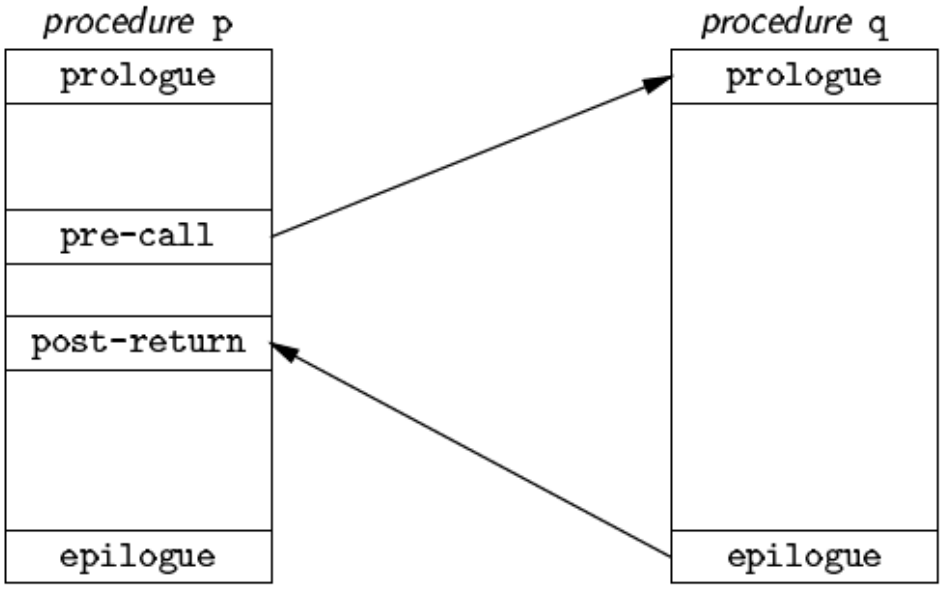
Linkages execute at run time

Code to make the linkage is generated at compile time

The procedure abstraction

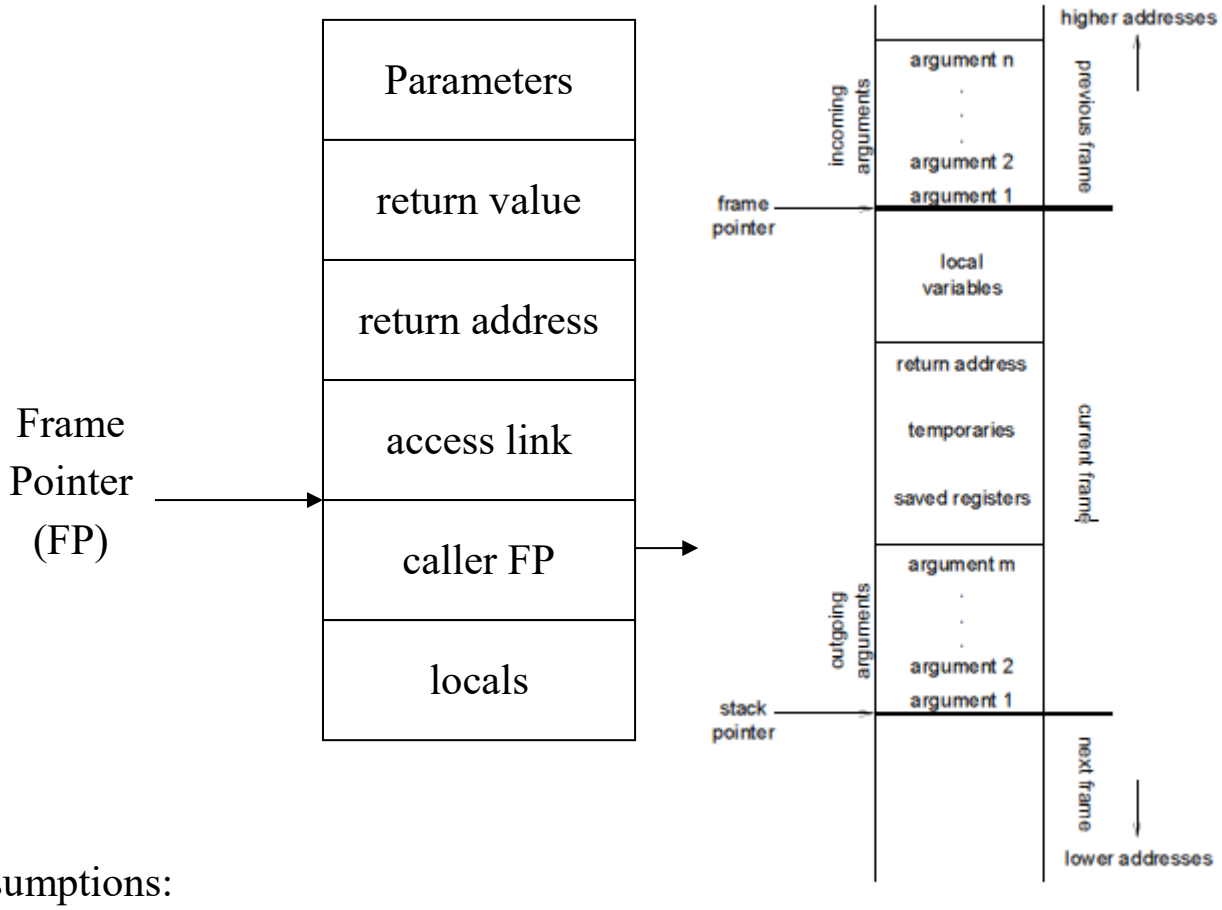
The essentials

- on entry, establish p's environment
- at a call, preserve p's environment
- on exit, tear down p's environment
- in between, addressability and proper lifetimes



Procedure linkages

Assume that each procedure activation has an associated activation record or frame(at run time)



Assumptions:

- call by reference parameter passing
- RISC architecture
- can always expand an allocated block
- locals stored in frame

Procedure linkages

The linkage divides responsibility between caller and callee

	Caller	Callee
Call	*pre-call* 1. allocate basic frame 2. evaluate & store params. 3. store return address 4. jump to child	*prologue* 1. save registers, state 2. store FP (dynamic link) 3. set new FP 4. store static link 5. extend basic frame (for local data) 6. initialize locals 7. fall through to code
Return	*post-call* 1. copy return value 2. deallocate basic frame 3. restore parameters (if copy out)	*epilogue* 1. store return value 2. restore state 3. cut back to basic frame 4. restore parent's FP 5. jump to return address

At compile time, generate the code to do this
At run time, that code manipulates the frame & data areas

Access to non-local data

Two important problems arise

1. How do we map a name into a (level, offset) pair?

   We use a block structured symbol table
   - when we look up a name, we want to get the most recent declaration for the name
   - the declaration may be found in the current procedure or in any nested procedure

2. Given a (level, offset) pair, what's the address?

   Two classic approaches
   - ⇨ access links(static links)
   - ⇨ displays

Access to non-local data

To find the value specified by (l, o)

- need current procedure level, k
- if k = l, is a local value
- if k > l, must find l's activation record
- k < l cannot occur

Maintaining access links: (static links)

- calling level k + 1 procedure
  1. pass my FP as access link
  2. my backward chain will work for lower levels
- calling procedure at level l < k
  1. find my link to level l – 1 and pass it
  2. its access link will work for lower levels

The display

To improve run-time access costs, use a display.

- table of access links for lower levels
- lookup is index from known offset
- takes slight amount of time at call
- a single display or one per frame
- for level k procedure, need k – 1 slots

Access with display
assume a value described by (l, o)

- find slot as DP + 4 * l
- add offset to pointer from slot

“setting up the base frame” now includes display manipulation.

display management

Single global display: complex, obsolete method,
bogus idea, do not use

call from level k to level l

if l = k + 1
add a new display entry for level k
if l = k
no change to display is required
if l < k
preserve entries for levels l through k – 1 in the local frame

on return (back in calling procedure)

if l < k
restore preserved display entries

A single display ties up another register

Display management

Single global display: simple method

Key insight – overallocate the display by one slot

on entry to a procedure at level l
    save the level l display value
    push FP into level l display slot

on return
    restore the level l display value

Quick, simple, and foolproof!

Display management

Individual frame-based displays:

call from level k to level l

if $l \leq k$

copy $l - 1$ display entries into child's frame

if $l > k$ ($l = k + 1$)

copy $k - 1$ entries into child's frame

copy own FP into k^{th} slot in child's frame

no work is required on return

⇨ display is deallocated with frame

Display is accessed by offset from FP

⇨ one less register required

Display versus access links

How to make the trade-off?

The cost differences are somewhat subtle

- frequency of non-local access
- average lexical nesting depth
- ratio of calls to non-local access

(Sort of) Conventional wisdom

tight on registers => use access links

lots of registers => use global display

shallow average nesting => frame-based display

Your mileage will vary

Making the decision requires understanding reality

Parameter passing

What about parameter?

Call-by-reference

- pass address of argument

Call-by-value

- pass values, not addresses
- never restore on return
- arrays, structures, strings are a problem

Call-by-value-result(copy-in/copy-out)

- pass values, not addresses
- always restore on return
- arrays, structures, strings are a problem

Call-by-name

- build and pass thunk
- access to parameter invokes thunk
- all parameters are same size in frame!

Parameter passing

What about variable length argument list?

1. if caller knows that callee expects a variable number
   A. caller can pass number as 0^{th} parameter
   B. callee can find the number directly
2. if caller doesn't know anything about it
   A. callee must be able to determine number
   B. first parameter must be closest to FP

Consider printf:

- number of parameters determined by the format of string
- it assumes the numbers match

Heap management techniques

Functionality:

- alloc(k) – allocates a block of at least k bytes in the free space pool, remove it from the pool, and returns its address
- free(p) – places the block pointed to by p back in the pool of free space for allocation

If unused storage is reclaimed, free is not needed.

Potential problems:

- wasted space – if alloc returns blocks that are larger than requested, the excess space is wasted
- fragmentation – after a series of alloc and free commands, the free space pool becomes fragmented, preventing allocation of large blocks
- speed – alloc and free should be inexpensive

A heap management scheme must balance these issues.

Heap management techniques

Scheme 1:

initialization

- start the free list with a single large block
- need two fields in each free block: size and next
- allocated blocks keep size field

alloc(k)

- find first block where $k + 4 \leq$ size
- no such block => report failure or get more space
- create block at k + 4 and put it on allocated list
- update free list
- return word of second word of allocated block

free(p)

- put p back on the free list

This is a first-fit scheme without coalescing

Heap management techniques

Problems with scheme 1:

1. over time, start of free list becomes dominated by small blocks
   solution: rover

2. blocks get too small to be useful
   solution: place a minimum size on blocks

3. overtime, large blocks get scarce
   solution: coalesce on free

Scheme 2:

initialization

- start the free list with a single large block
- set rover to start of free list

alloc(k)

- starting at rover, find first block that fits
- no such block => report failure or get more space
- split block into $2^{\lceil \log_2(k+4) \rceil}$ bytes and the rest
- place second block on free list, in address order
- return address of first block + 4

free(p)

- insert p on the free list, in address order
- if blocks before p is contiguous, coalesce with p
- if blocks after p is contiguous, coalesce with p.

First fit with rover, coalescing, bounded block size

Scheme 3:

- instead of finding first fit, find the best fit
- only split a block if size > k + threshold

Comparison

- best fit wastes less space
- best fit requires more allocation time

first fit => average case < size of free pool

best fit => average case is worst case

Heap management techniques

Modern allocators rely on several observations:

- large real and virtual memories are common
- speed is important
- sizes come in two flavors, common and unusual

Capitalizing on these facts, we can do better in practice.

Principles:

- separate pools for common sizes
- limit number of common sizes(2^i)
- use page size as upper bound on common size

Heap management techniques

A modern allocator:

- use separate free space pools for common sizes
  - 2^4 to 2^{12} (or page size)

- first fit within pool
  - alloc is O(1) + amortizing new page fragments
  - free is O(1), no coalescing, no order

- use a separate mechanism for larger regions
  - first fit over list of full pages
  - allocate only full size pages
  - coalesce on free to ensure contiguous blocks
  - O(n) alloc and free

Heap management techniques

A collecting allocator

- make free() automatic
- no pointer to a block -> done with it
- deallocate only when we run out of space

Simplifies programmer's life(important)

Observations

- either recognize pointers or be very conservative
- eliminate all those calls to free()
- add time for collection

Techniques

- reference counting
- marking algorithms
- copying collector