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Separate compilation:

- allows 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.

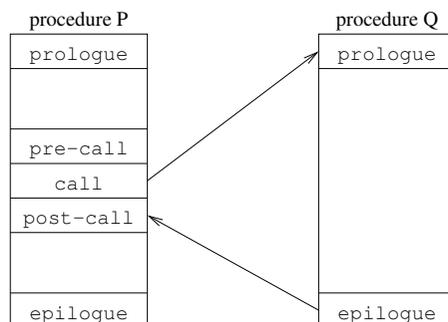
Linkages execute at run time

Code to make the linkage is generated at compile time



The 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

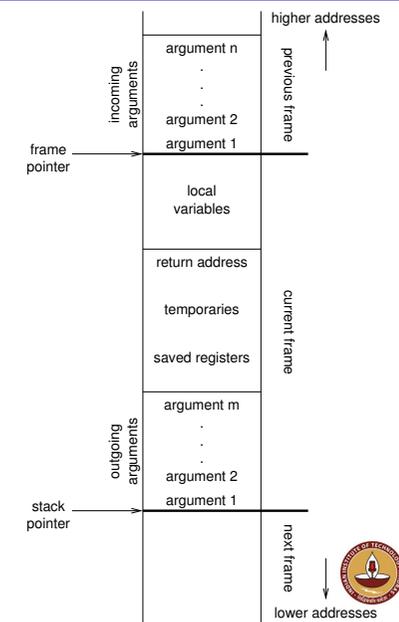


Each system has a standard linkage

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

Assumptions:

- 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	<u>pre-call</u> 1 allocate basic frame 2 evaluate & store params. 3 store return address 4 jump to child	<u>prologue</u> 1 save registers, state 2 store FP (dynamic link) 3 set new FP 4 store static link 5 extend basic frame 6 initialize locals 7 fall through to code
	Return	<u>post-call</u> 1 copy return value 2 deallocate basic frame 3 restore parameters (if copy out)

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



## Run-time storage organization

To maintain the illusion of procedures, the compiler can adopt some conventions to govern memory use.

### Code space

- fixed size
- statically allocated

(link time)

### Data space

- fixed-sized data may be statically allocated
- variable-sized data must be dynamically allocated

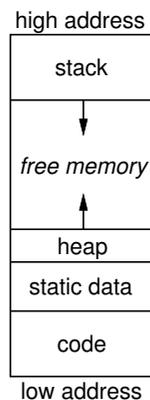
### Control stack

- dynamic slice of activation tree
- return addresses
- may be implemented in hardware



## Run-time storage organization

Typical memory layout



The classical scheme

- allows both stack and heap maximal freedom
- code and static data may be separate or intermingled



## Run-time storage organization

Where do local variables go?

When can we allocate them on a stack?

Key issue is lifetime of local names

Downward exposure:

- called procedures may reference my variables
- dynamic scoping
- lexical scoping

Upward exposure:

- can I return a reference to my variables?
- functions that return functions
- continuation-passing style

With only downward exposure, the compiler can allocate the frames of the run-time call stack



## Storage classes

Each variable must be assigned a storage class (base address)

Static variables:

- addresses compiled into code (relocatable)
- (usually) allocated at compile-time
- limited to fixed size objects
- control access with naming scheme

Global variables:

- almost identical to static variables
- layout may be important (exposed)
- naming scheme ensures universal access

Link editor must handle duplicate definitions



## Storage classes (cont.)

Procedure local variables

Put them on the stack

- if sizes are fixed
- if lifetimes are limited
- if values are not preserved

Dynamically allocated variables

Must be treated differently

- call-by-reference, pointers, lead to non-local lifetimes
- (usually) an explicit allocation
- explicit or implicit deallocation



## Access to non-local data

How does the code find non-local data at run-time?

Real globals

- visible everywhere
- naming convention gives an address
- initialization requires cooperation

Lexical nesting

- view variables as (level,offset) pairs (compile-time)
- chain of non-local access links
- more expensive to find (at run-time)



## Access to non-local data

Two important problems arise

- How do we map a name into a (level,offset) pair?  
Use a block-structured symbol table (remember last lecture?)
  - look up a name, want its most recent declaration
  - declaration may be at current level or any lower level
- Given a (level,offset) pair, what's the address?  
Two classic approaches
  - access links (or static links)
  - displays



## Access to non-local data

To find the value specified by  $(l, o)$

- need current procedure level,  $k$
- $k = l \Rightarrow$  local value
- $k > l \Rightarrow$  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 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 the display

assume a value described by  $(l, o)$

- find slot as `display[l]`
- add offset to pointer from slot (`display[l][o]`)

“Setting up the basic 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 1 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  $k^{\text{th}}$  slot in child's frame

No work required on return

- display is deallocated with frame

Display 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 parameters?

Call-by-value

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

Call-by-reference

- pass address
- access to formal is indirect reference to actual

Call-by-value-result

- store 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 lists?

- if caller knows that callee expects a variable number
  - caller can pass number as 0<sup>th</sup> parameter
  - callee can find the number directly
- if caller doesn't know anything about it
  - callee must be able to determine number
  - first parameter must be closest to FP

Consider `printf`:

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



## Calls: Saving and restoring registers

	caller's registers	callee's registers	all registers
callee saves	1	3	5
caller saves	2	4	6

- Call includes bitmap of caller's registers to save/restore (best with save/restore instructions to interpret bitmap)
- Caller saves and restores its own registers  
Unstructured returns (e.g., non-local gotos, exceptions) create some problems, since code to restore must be located and executed
- Backpatch code to save regs used in callee on entry, restore on exit e.g., VAX places bitmap in callee's stack frame for use on call/return/non-local goto/exception  
Non-local gotos and exceptions must unwind dynamic chain restoring callee-saved registers
- Bitmap in callee's stack frame is used by caller to save/restore (best with save/restore instructions to interpret bitmap directly)  
Unwind dynamic chain as for 3
- Easy: Non-local gotos and exceptions must restore all registers from "outermost callee"
- Easy (use utility routine to keep calls compact): Non-local gotos and exceptions need only restore original registers from caller



## Call/return

Assuming callee saves:

- caller pushes space for return value
- caller pushes SP
- caller pushes space for: return address, static chain, saved registers
- caller evaluates and pushes actuals onto stack
- caller sets return address, callee's static chain, performs call
- callee saves registers in register-save area
- callee copies by-value arrays/records using addresses passed as actuals
- callee allocates dynamic arrays as needed
- on return, callee restores saved registers
- jumps to return address

Caller must allocate much of stack frame, because it computes the actual parameters

Alternative is to put actuals below callee's stack frame in caller's: common when hardware supports stack management (e.g., VAX)



## MIPS procedure call convention

Registers:

Number	Name	Usage
0	zero	Constant 0
1	at	Reserved for assembler
2, 3	v0, v1	Expression evaluation, scalar function results
4-7	a0-a3	first 4 scalar arguments
8-15	t0-t7	Temporaries, caller-saved; caller must save to preserve across calls
16-23	s0-s7	Callee-saved; must be preserved across calls
24, 25	t8, t9	Temporaries, caller-saved; caller must save to preserve across calls
26, 27	k0, k1	Reserved for OS kernel
28	gp	Pointer to global area
29	sp	Stack pointer
30	s8 (fp)	Callee-saved; must be preserved across calls
31	ra	Expression evaluation, pass return address calls



## MIPS procedure call convention

Philosophy:

*Use full, general calling sequence only when necessary; omit portions of it where possible (e.g., avoid using fp register whenever possible)*

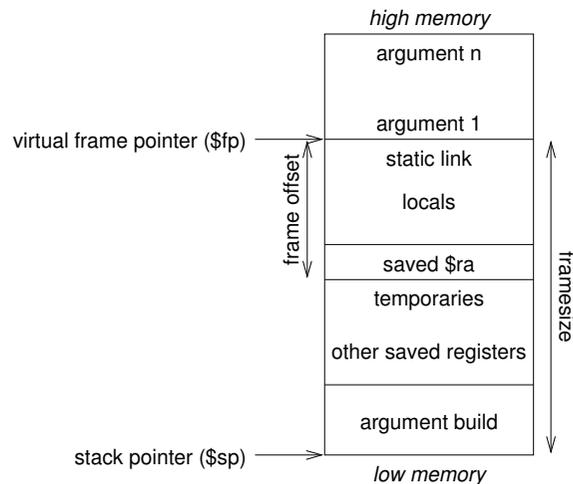
Classify routines as:

- non-leaf routines: routines that call other routines
- leaf routines: routines that do not themselves call other routines
  - leaf routines that require stack storage for locals
  - leaf routines that do not require stack storage for locals



## MIPS procedure call convention

### The stack frame



## MIPS procedure call convention

### Pre-call:

- 1 Pass arguments: use registers \$a0 ... \$a3; remaining arguments are pushed on the stack along with save space for \$a0 ... \$a3
- 2 Save caller-saved registers if necessary
- 3 Execute a `jal` instruction: jumps to target address (callee's first instruction), saves return address in register \$ra



## MIPS procedure call convention

### Prologue:

- 1 Leaf procedures that use the stack and non-leaf procedures:
  - 1 Allocate all stack space needed by routine:
    - local variables
    - saved registers
    - sufficient space for arguments to routines called by this routine

```
subu $sp, framesize
```

  - 2 Save registers (\$ra, etc.):

```
sw $31, framesize+frameoffset($sp)
sw $17, framesize+frameoffset-4($sp)
sw $16, framesize+frameoffset-8($sp)
```

where `framesize` and `frameoffset` (usually negative) are compile-time constants
- 2 Emit code for routine



## MIPS procedure call convention

### Epilogue:

- 1 Copy return values into result registers (if not already there)
- 2 Restore saved registers

```
lw reg, framesize+frameoffset-N($sp)
```
- 3 Get return address

```
lw $31, framesize+frameoffset($sp)
```
- 4 Clean up stack

```
addu $sp, framesize
```
- 5 Return

```
j $31
```

