Principles of Programming Languages

Lecture 06

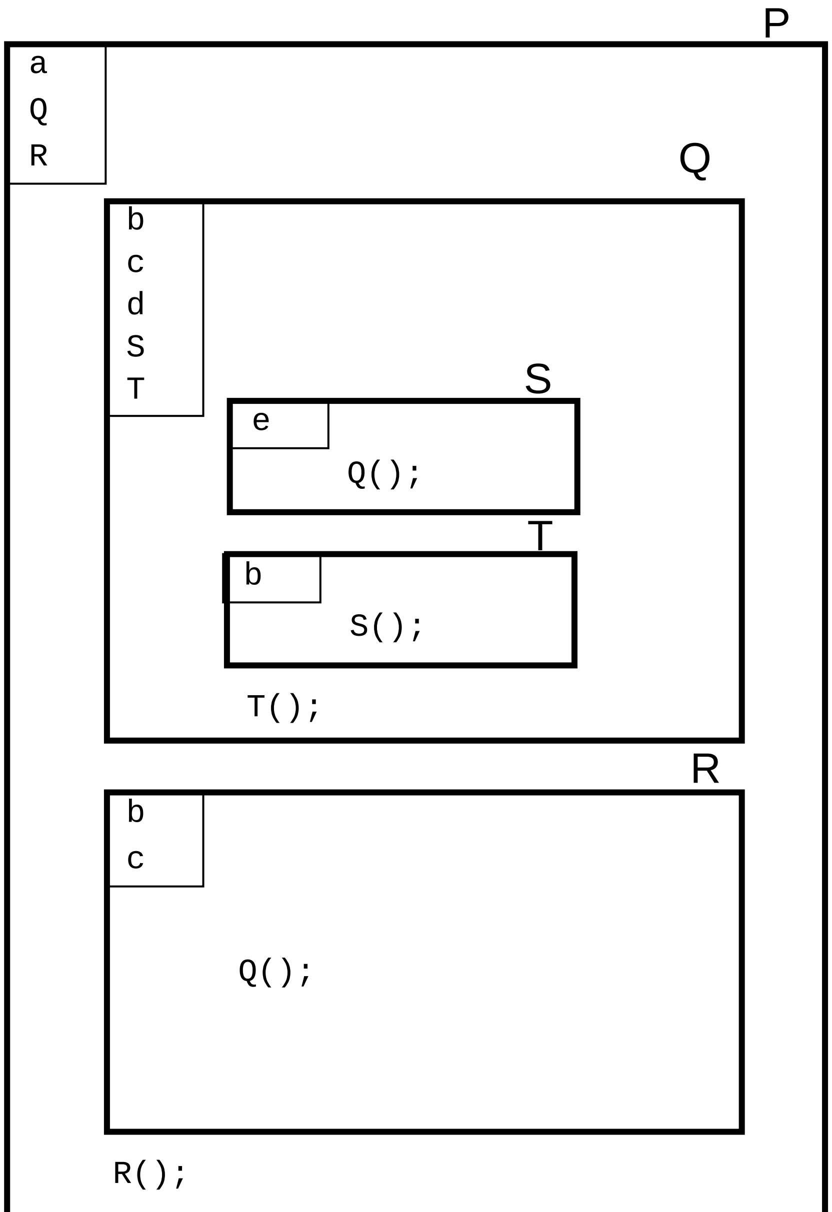
Implementation of

Block Structured Languages

Activations and Environment

- Aspects of Subroutines: Static vs Dynamic
  - Static subroutine: *code* (``reentrant'')
    - Exactly one subroutine
  - Subroutine in execution: *activation record, AR, activation*
    - Many activations of same code possible
- State of a program in execution
  - A collection of activations
    - In a stack or in a heap
  - Contextual relationships among the activations
    - ``environment access'' pointers & ``control'' pointers
- Activation contents
  - *Fixed*: program code (shared)
  - *Variable:* activation
    - Instruction pointer (*ip*, *ra*) —also *resumption address* or *return address*
    - Control Pointer (*dl*) —also *control link, dynamic link*
    - Environment pointer (*ep, fp*) —also *access link, frame pointer*
      - *Local* environment (this activation)—*fp*
      - *Nonlocal* environment (other activations)—*sl , static link*

Contour Diagram (Static) & RT Stack (Dynamic)

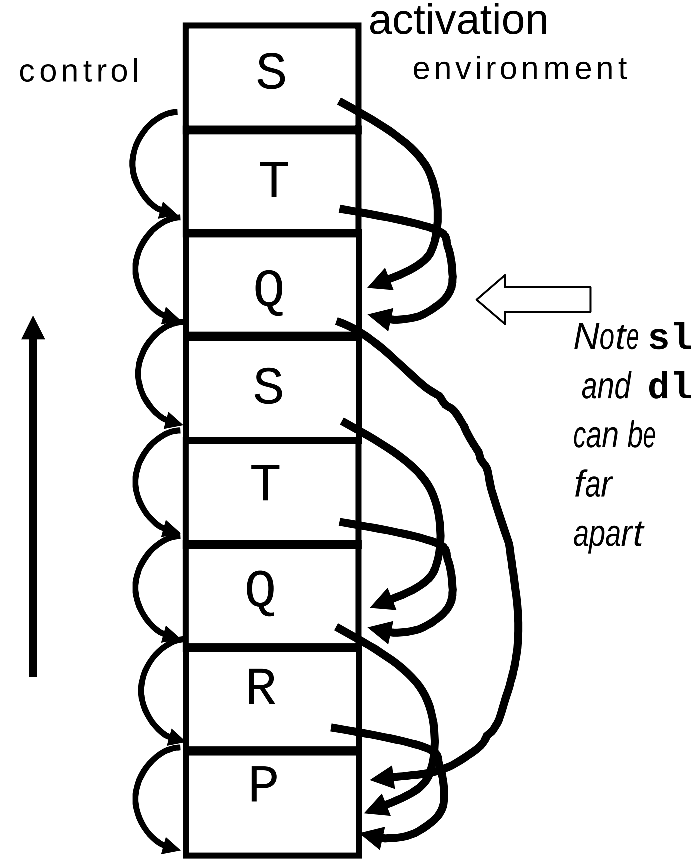


Assume static binding

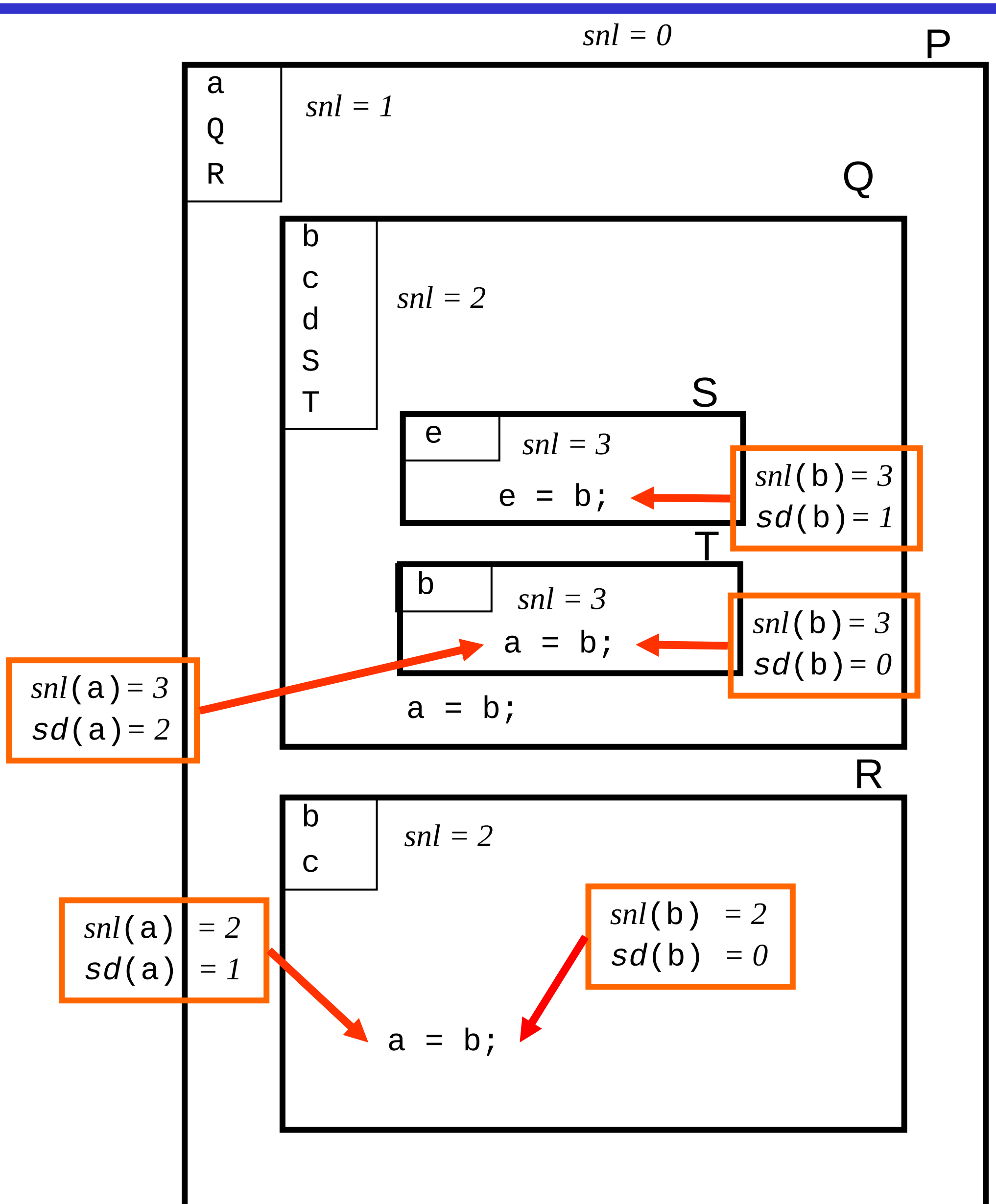
Calling trace: `P, R, Q, T, S, Q, T, S`

`dl` = dynamic link to caller at RT

`sl` = static link to statically enclosing activation



Static Nesting Level (*snl*) and Distance (*sd*)



snl(name declaration)
= # of contour lines surrounding declaration

snl(name reference)
= # contour lines surrounding reference

Static Distance of a Symbol Occurrence

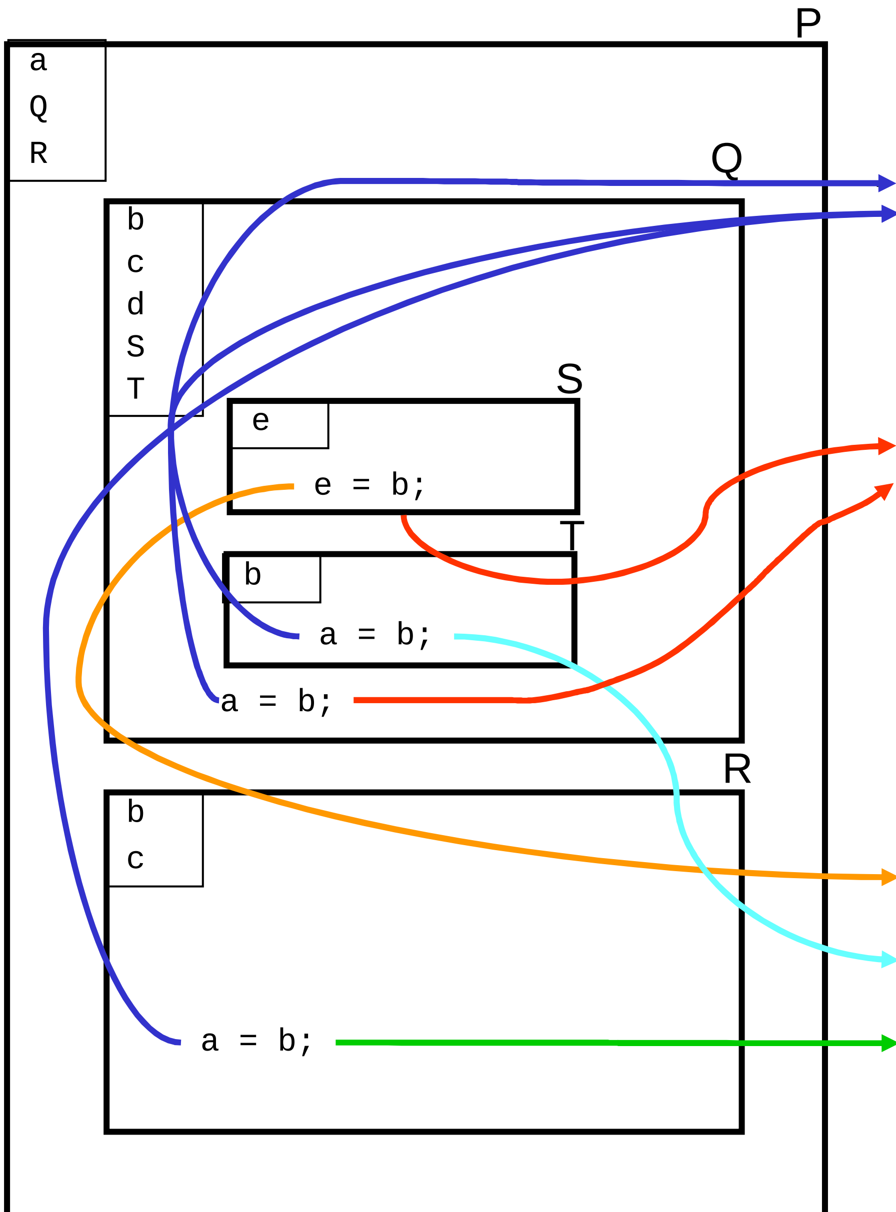
sd(name occurrence)
= # of contours crossed outward from occurrence to declaration
= *snl*(name's occurrence)
- *snl*(that name's decl.)

Symbol Table Computes *snl*

- Symbol table maps an *occurrence* of `x` to
  - line #
  - *snl* `(declaration)`
  - Offset among declarations
- Each name `x` has an ``address'': (line #, *snl*, offset)
- Scanner keeps track of
  - Contour boundaries crossed (e.g. +1 for `{` & -1 for `}`)
  - Current name declarations in scope
- Scanner can therefore
  - Identify declaration controlling a name occurrence
  - Replace a name occurrence by pointer to symbol table line #

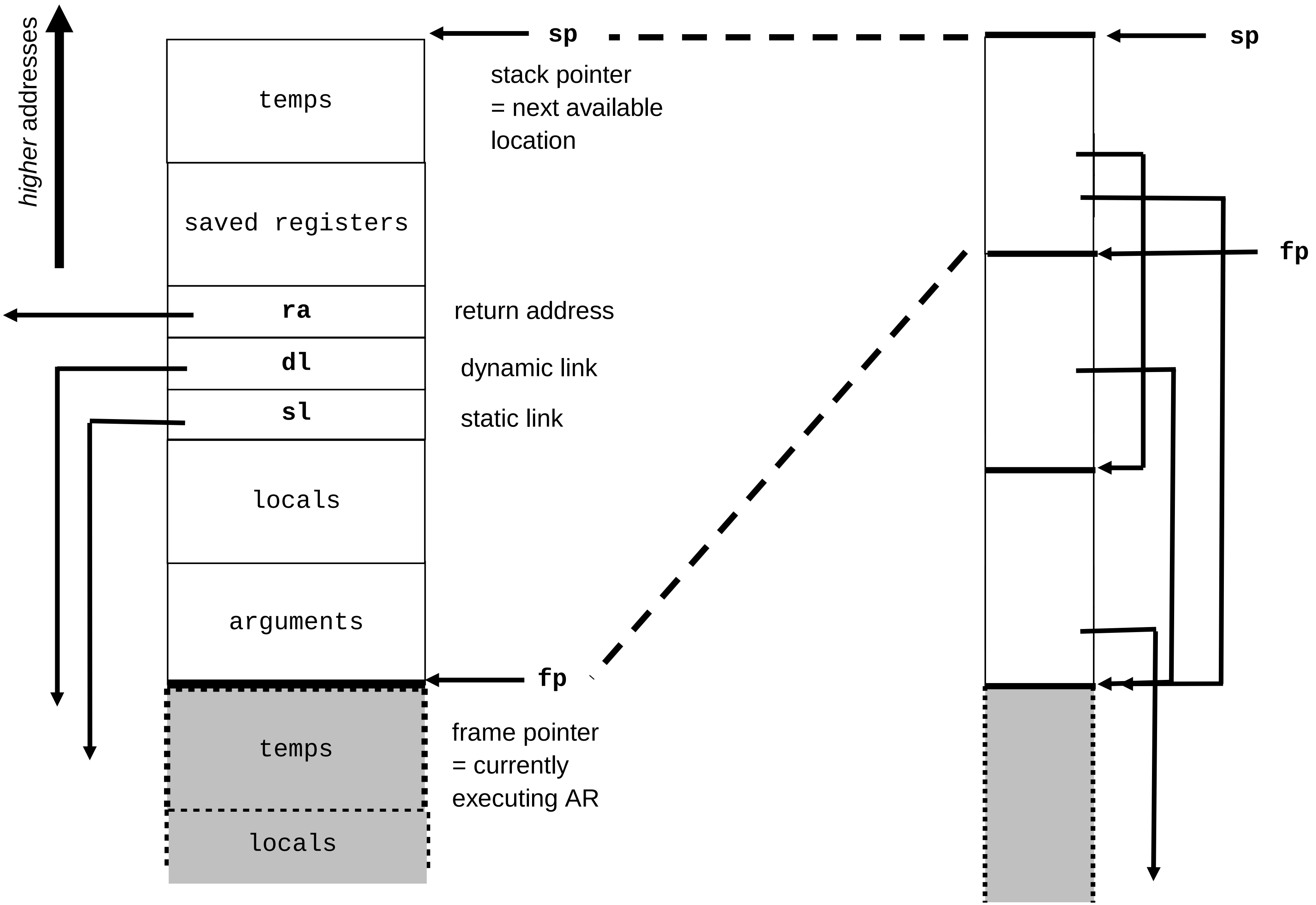
Symbol Table (cont.)

Assume for simplicity all variables are **int** and occupy one address



#	name	*snl*	offset	type &c ...
1	P	0	0	`int ()`
2	a	1	0	`int`
3	Q	1	1	`int (int)`
4	R	1	2	`int (int)`
5	b	2	0	`int`
6	c	2	1	`int`
7	d	2	2	`int`
8	S	2	3	`void (int)`
9	T	2	4	`int (int)`
10	e	3	0	`int`
11	b	3	0	`int`
12	b	2	0	`int`
13	c	2	1	`int`

Activation Record Stack



Activation Record Stack

- Model an AR by a struct (pretend all data are **`int`** for simplicity)

```
struct AR {
    int arg[n];
    int local[m];
    AR* sl;
    AR* dl;
    CODE* ra;
    void* rx;          —register save area
    ...
}
```

- Temps are pushed on top (``frame extension'') during execution in the activation record and are abandoned on return
- Assume stack growth to *higher* addresses (in reality usually the other way)

Registers

- Special purpose registers: **`ra, sp, fp`**
- General purpose registers divided into two classes
  - *Caller-saves:* transient values unlikely to be needed across calls
    - Callee assumes nothing valuable in caller-saves set & can be used at will (“destroyed”)
    - **Ex:** temp values during expression evaluation in caller
    - Caller saves these during calling sequence and they are restored after subroutine return
  - *Callee-saves:* used for local variables and indexes, etc.
    - Caller assumes these registers will not be destroyed by callee
    - **Ex:** register holding pointer during a list scan
    - Callee saves these in the prologue just after call, and restores in the epilogue just before return

Compiler Code Generation

- What is generated at CT (to be executed at RT):
  - Upon reference to a variable name **`x`**?
  - In caller before call to subroutine **`Q`** & after return to caller—the *calling sequence*?
  - In callee before execution of body?
    - Prologue
  - In callee before return to caller?
    - Epilogue
- Assume we are generating code inside body of a subroutine named **`P`**
  - Compiler maintains a level counter during code generation: `curr_level` = current static nesting level of site where code is being generated (body of **`P`**)

Access (Reference) to **x** inside **P**

- From symbol table compiler can compute:
  - **x** $\rightarrow$ *snl*(**x**), *offset*(**x**)
  - **P** $\rightarrow$ *snl*(**P**)
  - `curr_level =` *snl*(**P**) + 1 (level at which ref occurs)
  - *sd*(**x**) = `curr_level -` *snl*(**x**)
- Generate code to compute *l*-value into **lv**:
  - **ap** = activation record ptr

```
ap = fp;
for(i = 0; i < sd(x); i++) ap = ap->sl ;
lv = ap + offset(x);
```

  - Use **lv** on LHS of assignment, ***lv** on RHS

Call **`Q`** inside **`P`**

- Calling sequence for **`` ``call Q'' ``** in source
- Assume arguments passed by value

`sp->arg[1] =` *value of argument 1* **`;`** —transmit args

`. . .`

`sp->arg[`*n***`] =`** *value of argument n***`;`**

`fp->ra= resume ;` —set point to resume execution in caller

`sp->dl = fp;` —set callee's return link

`fp->ry = ry ; …;` —save caller-saves registers

`ap = fp;` —find AR of callee **`Q's`** declaration

`for(i = 0; i <` *sd***`(Q); i++) ap = ap->sl ;`**

`sp->sl = ap;` —set callee's static link

`fp = sp;` —switch to new environment

`goto` *entrypoint***`(Q);`** —from symbol table, after **`Q`** is compiled

`resume: …`

- note stack has not been pushed (callee's responsibility)

Prologue Code for Subroutine **`Q`**

- Code executed just after caller jumps to callee
- Note compiler knows size of AR for **`Q`**

  `sp = sp +` *size*(**AR** of **Q**) **`;`** —push stack frame for current activation

  `fp->rx = rx; … ;` —save any callee-saves registers

  - now **`sp`** points to next available stack location
  - now **`fp`** points to subroutine frame base
- Push could be done by caller (caller knows name of **`Q`** at CT)
  - But this will not work for closures (see below) where caller *does not know name of callee at CT*

Epilogue code for Subroutine **Q**

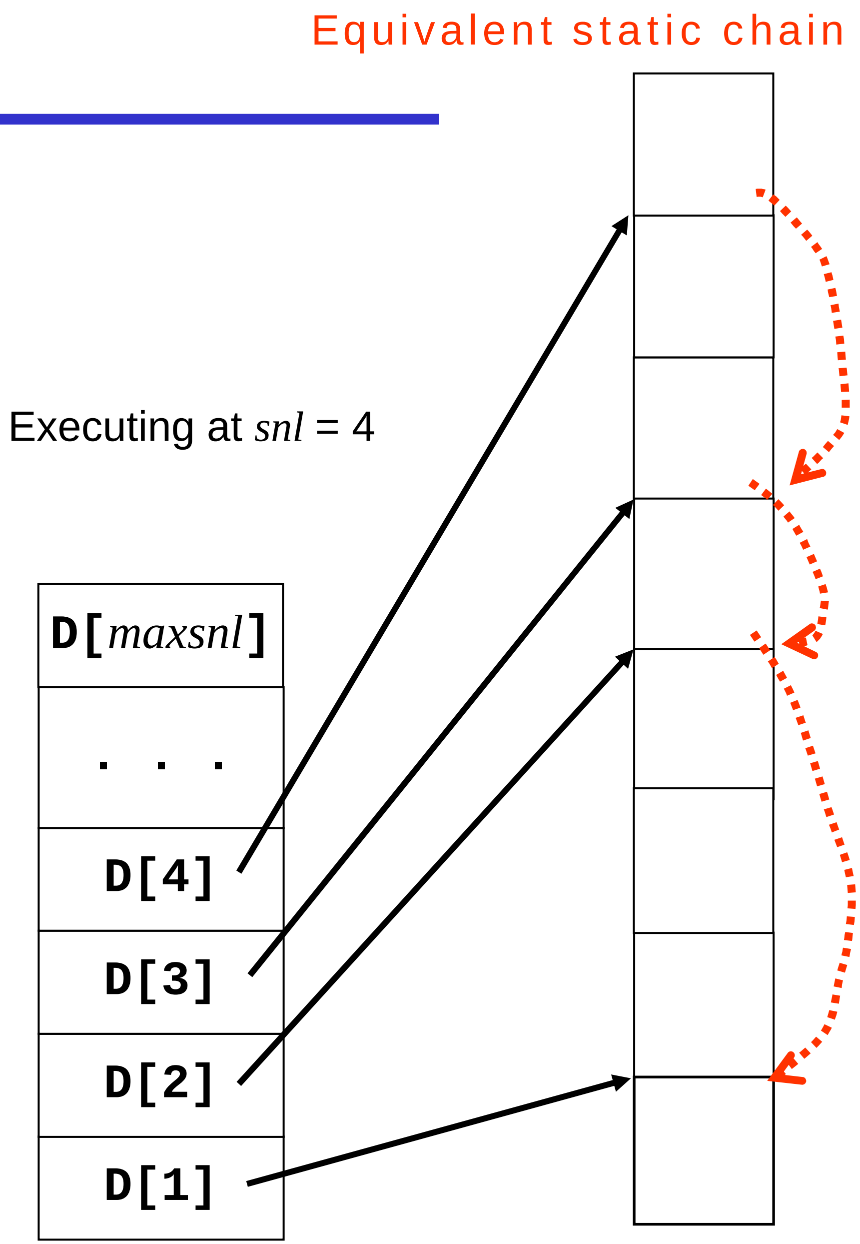
- Code executed just before return to caller
- Note compiler knows size of AR for **Q**

`rx = fp->rx`	—restore any callee-saves registers
`sp = sp -` *size*(**AR** of **Q**) **`;`**	—pop stack frame for current activation
`fp = fp->dl;`	—make caller's activation current one
`ry = fp->ry; … ;`	—restore caller-saves registers
`goto fp->ra;`	—resume execution in caller just after point of call

- now **`sp`** points to next available stack location
- now **`fp`** points to frame base of caller

Display Method

- Linked list replaced by array!
- Replace traversal of static chain by a single memory reference—more efficient calculation of non-local environment references
- At CT, the maximum static nesting level is known; possible *snl* values are *1 .. maxsnl*
- The display is an array **D** of *maxsnl* elements
- **D[i] = fp** for that part of the environment that is in an AR at *snl* **i**



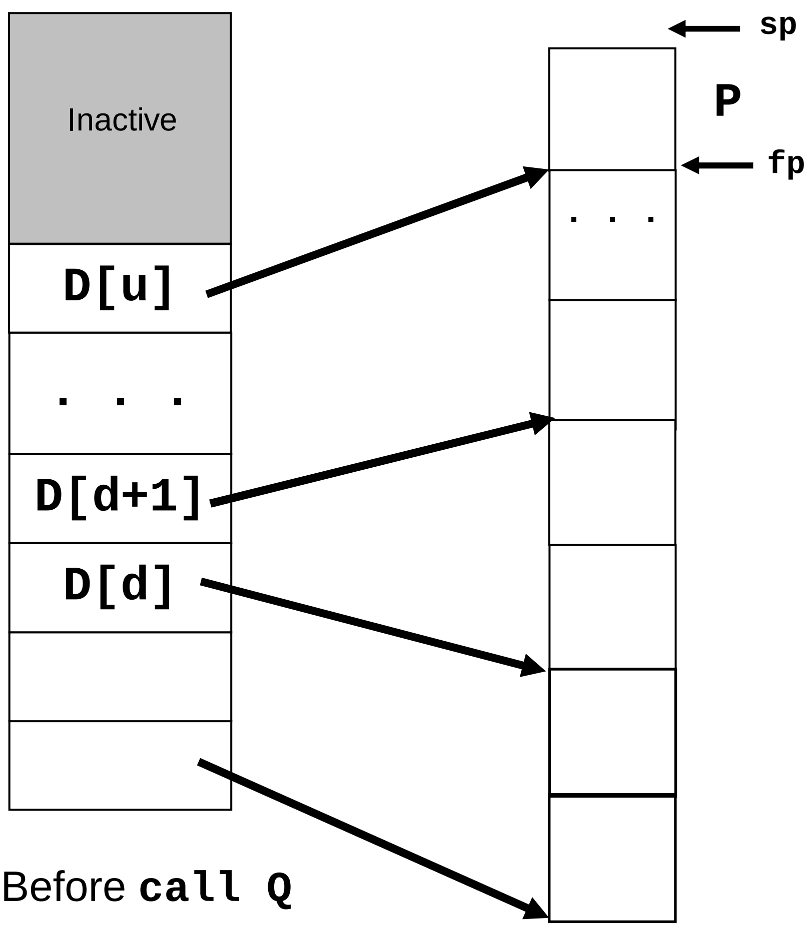
Access (Reference) to **x** inside **P**

- Generate code to compute *l*-value into **lv**:

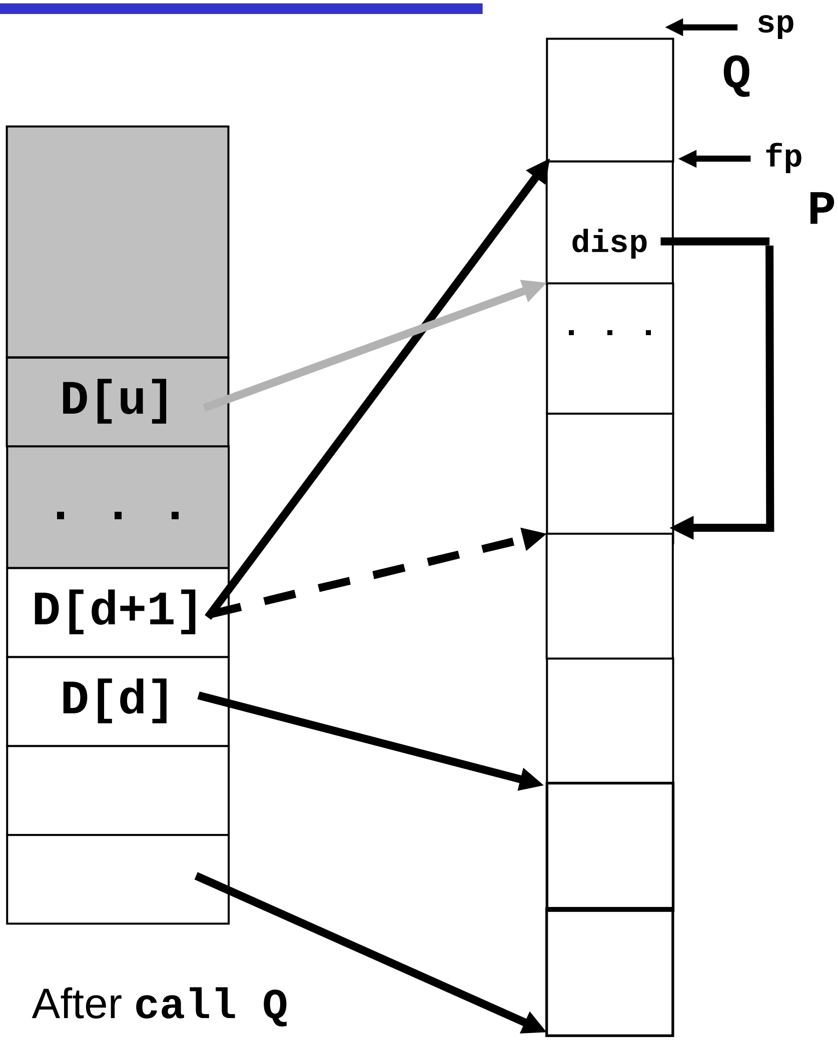
  lv = *D[*snl***(x)]+** *offset***(x)**

  - Use **lv** on LHS of assignment, ***lv** on RHS

Call **`Q`** inside **`P`**



Before **`call Q`**
Executing at *snl* = *u* in **`P`**
Subr. **`Q`** defined at *snl* = *d* ≤ *u*



After **`call Q`**
Executing at *snl* = *d* + 1
(body of **`Q`** one level deeper)
`D[d+1]` overwritten to point to new AR

Call `Q` inside `P` (cont.)

- **`Q`** defined at $snl\ d \Rightarrow$ new AR executes at $snl\ d{+}1 \Rightarrow$ **`D[d+1]`** points to new AR for **`Q`**
- Old **`D[d+1]`** (dotted link) destroyed
- Saved in *caller*'s AR (since part of caller's display)
  - New **`AR`** field **`fp->disp`**
- Other elements **`D[i]`** where $i \geq d + 2$ left alone
  - An AR deeper in the stack might need them upon return

Call **Q** inside **P** (cont.)

- Calling sequence for **``call Q''** in source
- Let **u** = *snl*(**P**) **&** **d** = *snl*(**Q**)
  - Note **fp == D[u]**

sp->arg[1] = *value of argument 1* **;** —transmit args

. . .

sp->arg[*n***] =** *value of argument n***;**

fp->ra= resume ; —set return point in caller

sp->dl = fp; —set callee's return link

fp->ry = ry; …; —save caller-saves registers

fp->disp = D[d+1];—save caller's display entry to reset on return

D[d+1] = sp; —set display for callee; **D[1..d]** are shared

fp = sp; —switch to callee environment

goto *entrypoint***(Q);** —from symbol table, after **Q** is compiled

resume: …

Prologue/Epilogue code for Subroutine **Q**

- Prologue same as before

  `sp = sp +` *size*(**AR** of **Q**) **`;`** —push stack frame for current activation

  `fp->rx = rx;…;` —save any callee-saves registers

- Epilogue restores caller's display
  - Let *u* = *snl*(**Q**) —this is known to compiler

  `rx = fp->rx; …;` —restore callee-save registers

  `sp = sp -` *size*(AR of **Q**) **`;`** —pop stack frame for current activation

  `fp = fp->dl;` —make caller's activation current

  `D[u] = fp->disp;` —restore caller's display

  `ry = fp->ry; … ;` —restore caller-saves registers

  `goto fp->ra;` —resume execution in caller just after point of call

Costs: Static Chain vs Display

- Compare count of memory references
  - Exclude argument transmission, reg. saves (common to both)
  - Assume **`fp, sp`** held in registers
- Analyze calling sequence for static chain

instruction	# refs
`fp->ra= resume;`	**1**
`sp->dl = fp;`	**1**
`sp->ry = ry; … ;`	**-**
`ap = fp;`	**0**
`for(i = 0; i <` *sd*(**`Q); i++) ap = ap->sl;`**)	*sd*(**Q**)
`sp->sl = ap;`	**1**
`fp = sp;`	**0**
`goto` *entrypoint*(**`Q);`**)	**0**
	sd(**Q**)**+3**

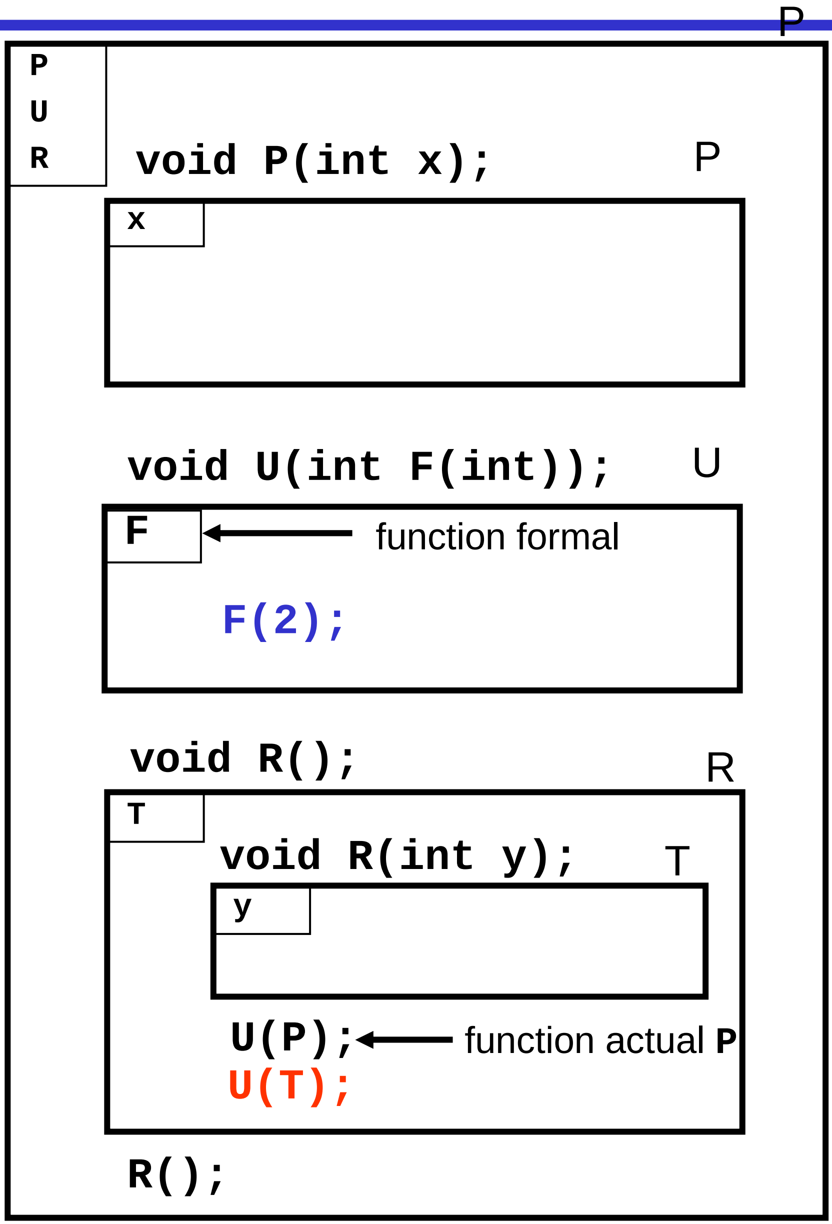
Costs (cont.)

- Comparison by # memory references:

Operation	Static chain	Display
Access local *l*-value	1	1
Access non-local **x** *l*-value	*sd*(**x**)	2
Call **Q**	*sd*(**Q**)+ 3	5
Q Prologue	0	0
Q Epilogue	3	5

- Need lots of *sd*(**x**)> 2 & *sd*(**Q**)> 2 to make worth it

Funargs (Procedure/Function Arguments)



- Consider call **U(T);** (both **U** and **T** are visible in body of **R**)
- **T** is not visible to **U** ⇒ no **T** activation in the static chain of **U** ⇒ at the call **T(2)** in **U**, cannot locate definition environment of **T**!
- How is the call **F(2)** implemented?
  - Must work for *any* **F** actual
- What is passed to **U** in **U(T)?**

Funargs (cont.)

- Consider call `F(2);` Previous calling sequence cannot be used. Missing information shown in blue:

```
sp->arg[1] = value of argument 1 ; … ;   —transmit args
fp->ra= resume ; —set return point in caller
sp->dl = fp;     —set callee's return link
fp->ry = ry ; …;        —save caller-saves registers
ap = fp;              —find AR of callee F's declaration
for(i = 0; i < sd(F); i++) ap = ap->sl ;
sp->sl = ap;      —set callee's static link
fp = sp;              —switch to new environment
goto entrypoint(F); —from symbol table, after F is compiled
resume: …
```

Don't know what F really is at CT and don't know *sd*(F) and *entrypoint*(F)

Calling a Formal: `F(…);` inside **`U(F)`**

- sd(**`F`**) is unknown at CT
- At RT, the actual functional argument need not even be in **`U`**'s static chain $\Rightarrow$ it is inaccessible from the current AR
- $\therefore$ environment of definition of each funarg must be passed to **`U`** as part of actual argument
- A *funarg* or *closure* is a pair (ip, ep) where:
  - ip = entry address of the actual argument procedure
  - ep = reference to most recent activation of definition environment of actual argument procedure

Closure Implementation

- A closure is a pair of references:

```
struct CL {
      CODE* ip;          —instruction pointer (entrypoint)
      AR*   ep;          —environment pointer
  }
```

- Closure **`f`** is built in caller when a <u>named</u> procedure is passed as an actual
- **`f`** is copied to callee **`U`** as actual corresponding to formal **`F`** : effectively ``**`F = f`**''
- When **`U`** calls **`F`**, the static link in the new activation is set by **`sp->sl = F.ep`** and the jump is by **`goto F.ip`**

Call **F** inside **U**

- Calling sequence for **``call F''** in source where **F** is a function formal

```
sp->arg[1] = value of argument 1 ;          —transmit args
. . .
sp->arg[n] = value of argument n;
fp->ra= resume ;  —set return point to resume execution
sp->dl = fp;      —set callee's return link
fp->ry = ry ; …;          —save caller-save registers
  ap = fp;               —find AR of callee Q's  declaration
  for(i = 0; i < sd(Q); i++) ap = ap->sl ;
sp->sl = F.ep;    —set callee's static link
fp = sp;              —switch to new environment
goto F.ip;        —entrypoint of code of actual
resume: …
```

Constructing and Passing Closure

- Consider call **U(T)** in AR for **R**
- Case: actual proc **T** is visible, named proc & so is **U**

sp->arg[*1***].ip =** *entrypoint***(T);**

fp->ra= resume ; —set return point to resume execution

sp->dl = fp; —set callee's return link

fp->ry = ry ; …; —save caller-save registers

ap = fp; —find AR of argument **T's** declaration

for(i = 0; i < *sd***(T); i++) ap = ap->sl ;**

sp->arg[*1***].ep = ap;** —environment of **T** set in callee

ap = fp; for(i = 0; i < *sd***(U); i++) ap = ap->sl ;**

sp->sl = ap; —set callee's static link

fp = sp; —switch to new environment

goto *entrypoint***(U);** —from symbol table

resume: …

Prologue/Epilogue Code

- Same as for ``named'' calls, since code is generated once for each possible named actual such as **T**
- Information for allocation/deallocation known at CT for **T**

Calls with Formal Procedures: Cases

- Let **`F, F’`** name formal functional parameters and let **`U`** name a visible, actual proc
- Discuss implementation of calling sequences for each of:
  - **`U(F);`**
  - **`F(T);`**
  - **`F(F’);`**

Calls with Formal Procedures: **F(T)**

- Call to a formal proc with an actual visible named proc

```
sp->arg[1].ip = entrypoint(T);
ap = fp;                 —find AR of argument T's declaration
for(i = 0; i < sd(T); i++) ap = ap->sl ;
sp->arg[1].ep = ap;          —environment of T set in callee
fp->ra= resume ;  —set return point to resume execution
sp->dl = fp;         —set callee's return link
fp->ry = ry ; …; —save caller-save registers
ap = fp;  for(i = 0; i < sd(F); i++) ap = ap->sl ;
sp->sl = ap;       —set callee's static link

sp→sl = F.ep;                —set callee's static link
fp = sp;               —switch to new environment
goto F.ip;              —from closure of F
resume: …
```

Challenge

- Can we implement functional parameters using the display?
  - Where does **`F`** get its display? (No static chain to unravel given only a starting environment **`F.ep`**)
  - How is display restored upon return?

Blocks

- Extend existing environment: **`{ int x; . . . }`**
- Special case of subroutine:
  - No parameters
  - No name
  - Called in one place—where defined
  - Statically prior env. (surrounding block) == dynamically prior

surrounding …

```
{ float x,y;
      x = z; y = 3;
      w = y;
 }
```

… ***block***

```
void function B();
{ float x, y;
      x = z; y = 3;
      w = y;
}
```

surrounding …

```
B();
```

… block

Block Activation/Deactivation

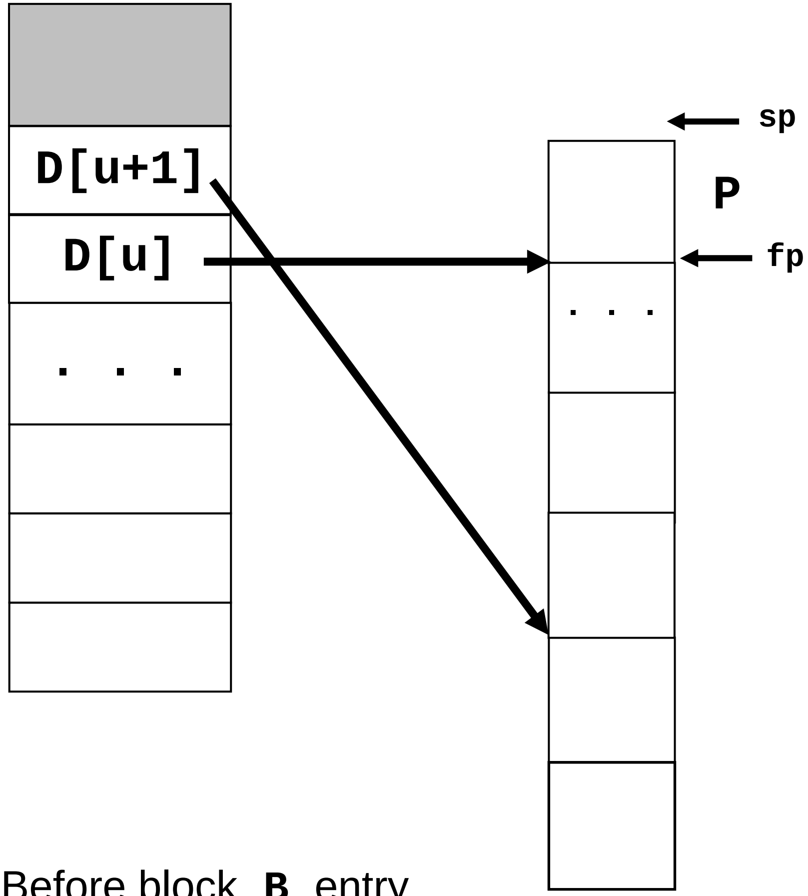
- A block is like a procedure, but
  - Nameless (because called from only one place)
  - Parameterless
  - Defined at its point of invocation (inline text)
  - Same static binding rules apply (static link == dynamic link)

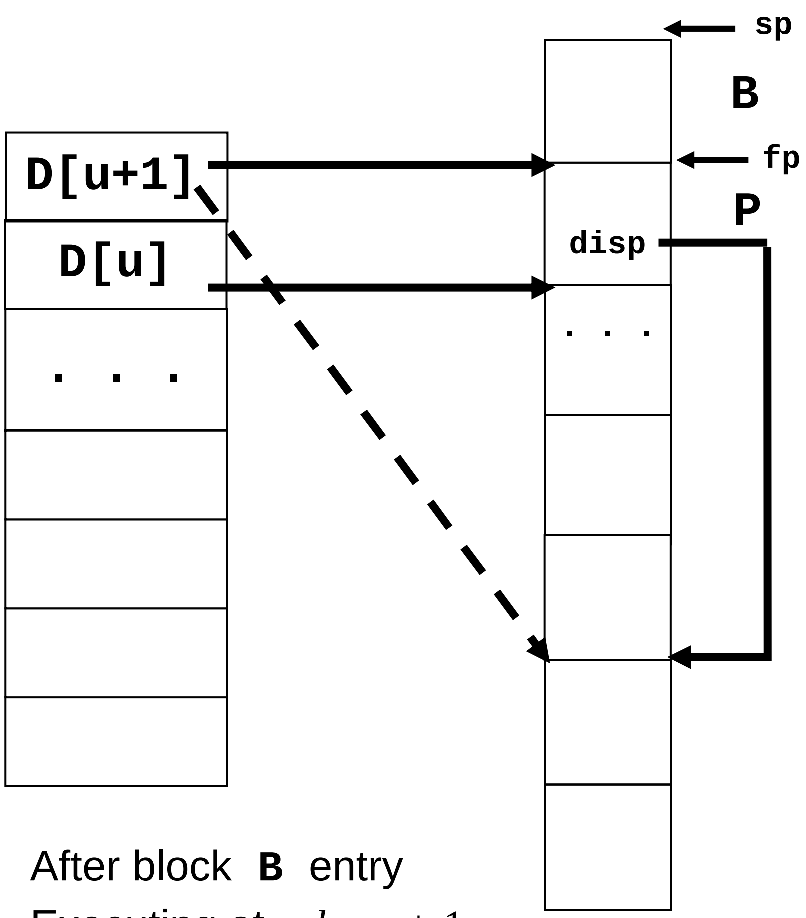
```
sp->sl = fp;        —set callee's return link
fp = sp;            —switch to new environment
sp = sp + size(AR of B) ; —push stack frame for block activation

entrypoint(B): …
              . . . Body of B . . .
sp = sp - size(AR of B) ; —pop stack frame for current activation
fp = fp->sl;              —reactivate containing block
resume: …
```

- Why are references in body of **B** resolved correctly?
- Can remove need for new AR by allowing caller's AR to grow and shrink

Exercise

- Show how to handle block entry/exit with using the display method





Before block **B** entry
Executing at *snl* = *u* in **P**

After block **B** entry
Executing at *snl* = *u* + 1
(body of **B** one level deeper)
D[u+1] overwritten to point to new AR

Solution to Exercise:

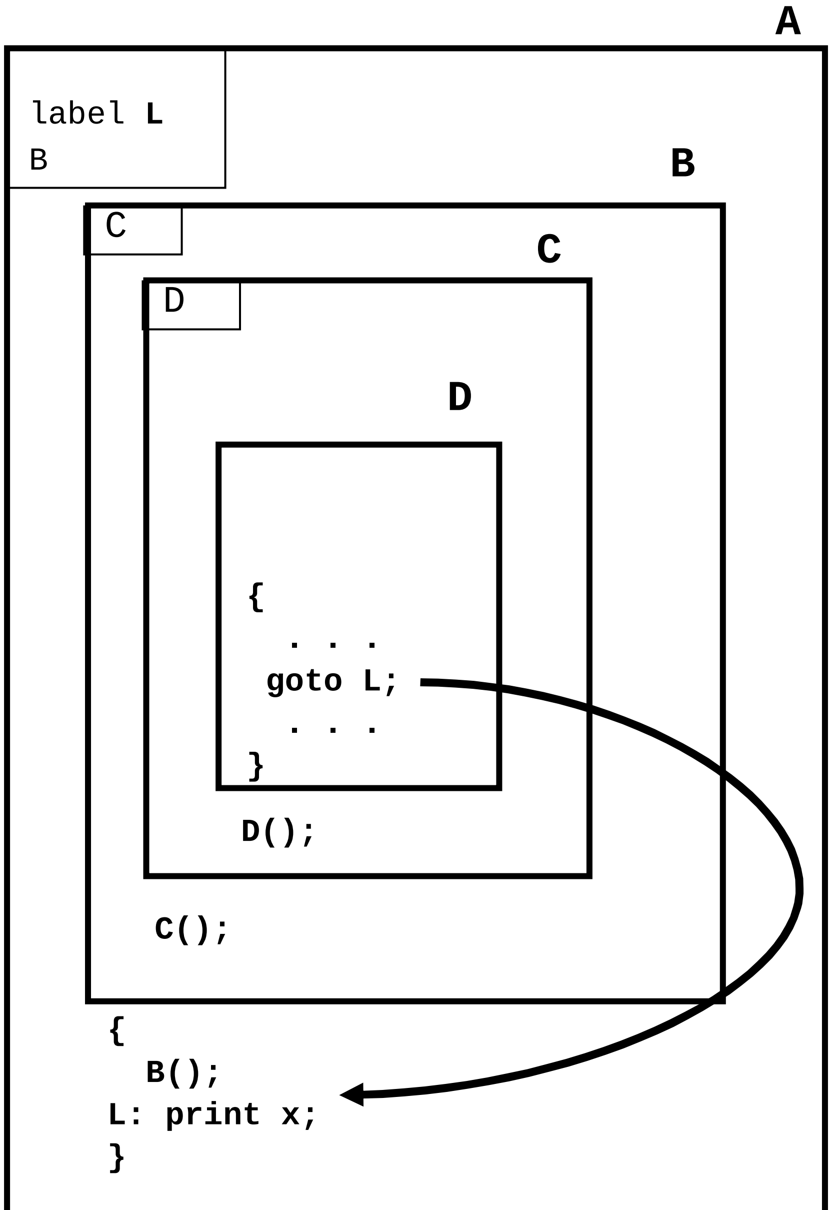
```
fp->disp = D[u+1];     —save caller's display entry
D[u+1] = sp;           —set callee's display
fp = sp;               —switch to new environment
sp = sp + size(AR of B) ;  —push stack frame for block activation
entrypoint(B): …
        . . . Body of B . . .
sp = sp - size(AR of B) ;  —pop stack frame for current activation
fp = D[u];             —reactivate containing block
```

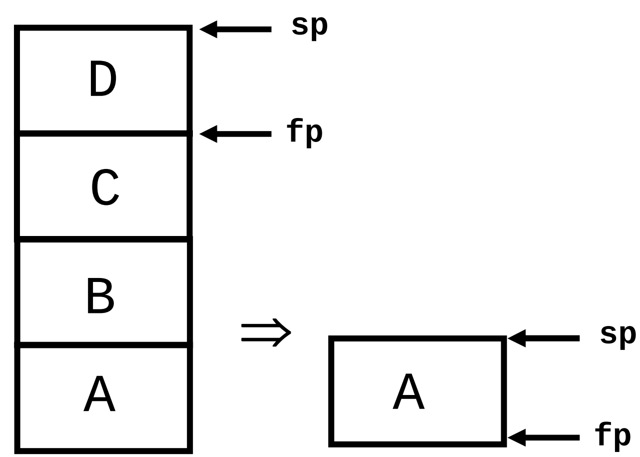
optimization

```
fp = sp - size(AR of P) ;  —reactivate containing block
```

```
D[u+1] = fp->disp;     —restore  caller's display
resume: …
```

Non-local **goto**'s





- *sd*(**L**) = *snl*(use **L**)– *snl*(def **L**)
  = *snl*(**D**)+1 – *snl*(**L**)

```
ap = fp;
for(i = 0; i < sd(L); i++)
   ap = ap->sl ;
fp = ap;
sp = fp + size(AR of A) ;
goto  address(L);
```

- What if display is used? How restore environment of **A?**

Label Scope Rules Vary

```
/*  In C, labels have entire function as scope */
#include <stdio.h>
main()
{       int i = 3;  int n = 10;   printf("before forward jump i = %d\n", i);
        goto fore;
back:   printf("after back jump i = %d\n", i);
        if (n < 3) {      int i = 7; int j = 13;
                fore:   i = i + 1;
                        printf("after forward jump i = %d\n", i);
                        printf("after forward jump j = %d\n", j);
                        goto back;
                }
        else    {       int i = 99;  printf("after else i = %d\n", i);
                }
        printf("before return i = %d\n", i);
}
```

Label Scope Rules (cont.)

```
opu> cc labels.c
opu> a.out
before forward jump i = 3
after forward jump i = 1
after forward jump j = 0
after back jump i = 3
after else i = 99
before return i = 3
opu>
```

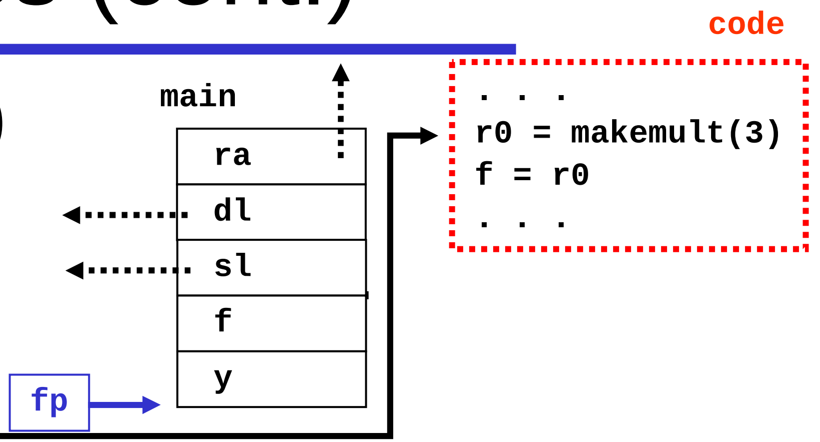
Returned Subroutines

```
main()
{
  int(int)  makemult(int n)
  {
     int t(int x){ return n*x; };
     return t;
  }
  int(int) f;
  int y;
  f = makemult(3);
  y = f(2);
}
```

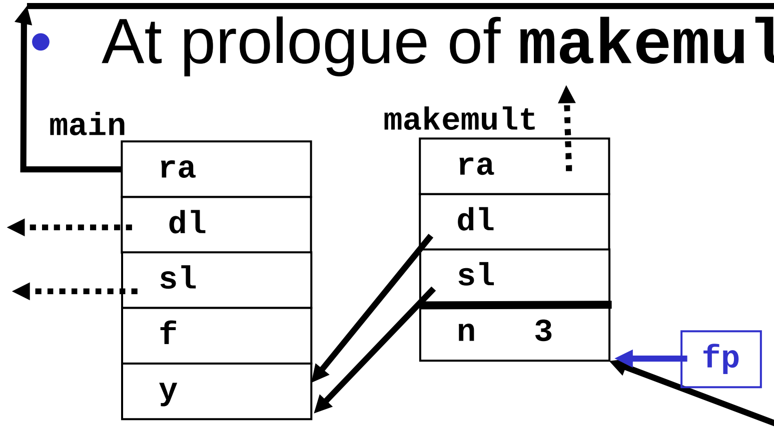
Returned Subroutines (cont.)

- Before call to **`makemult(3)`**
  - null pointer = ········▶

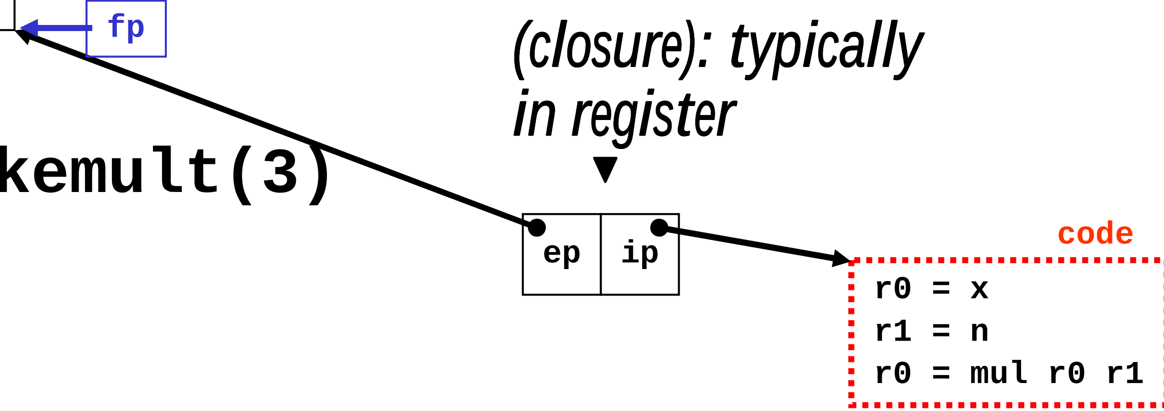
  frame pointer = fp ▶



- At prologue of **`makemult(3)`**

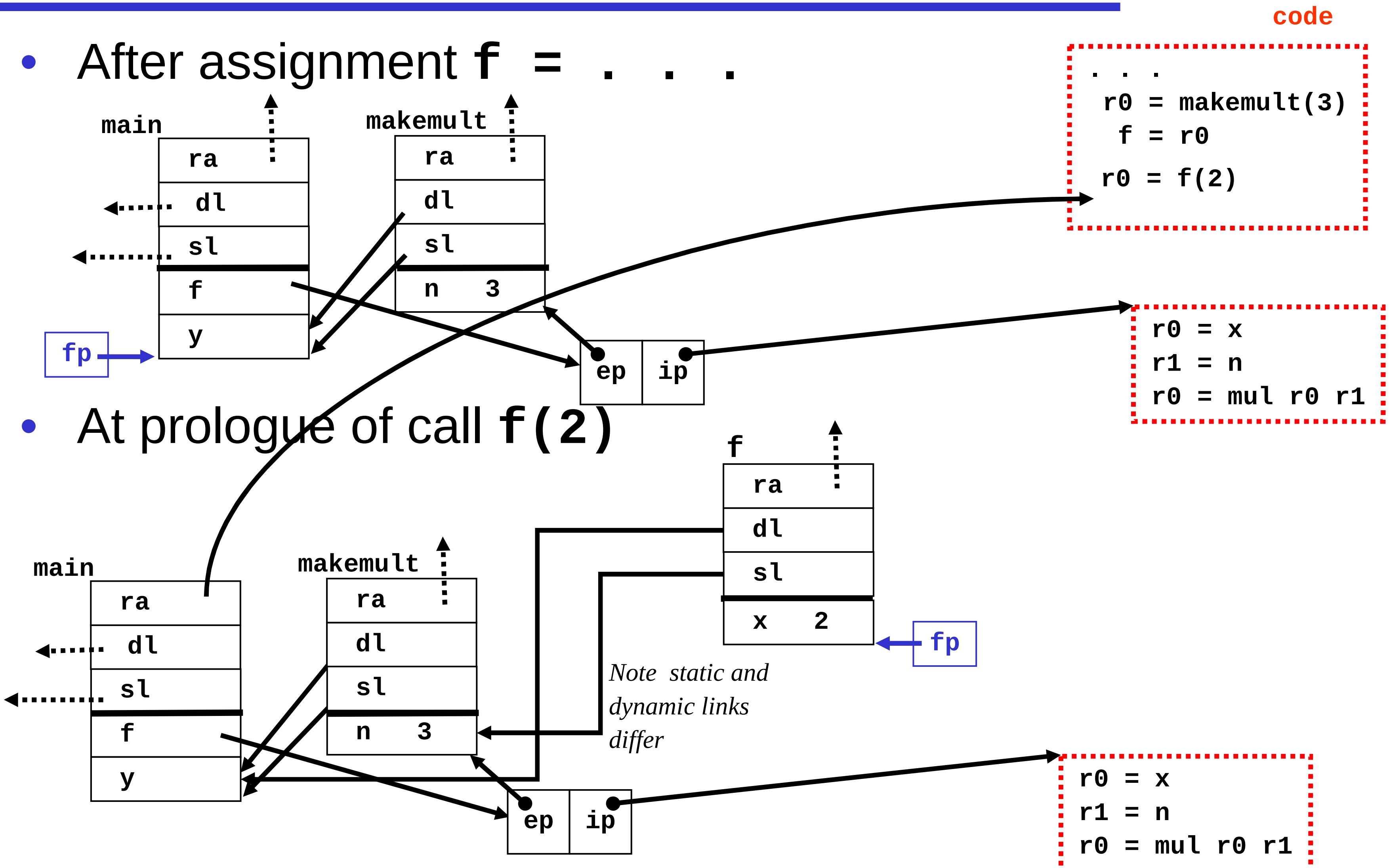


- At return from **`makemult(3)`**



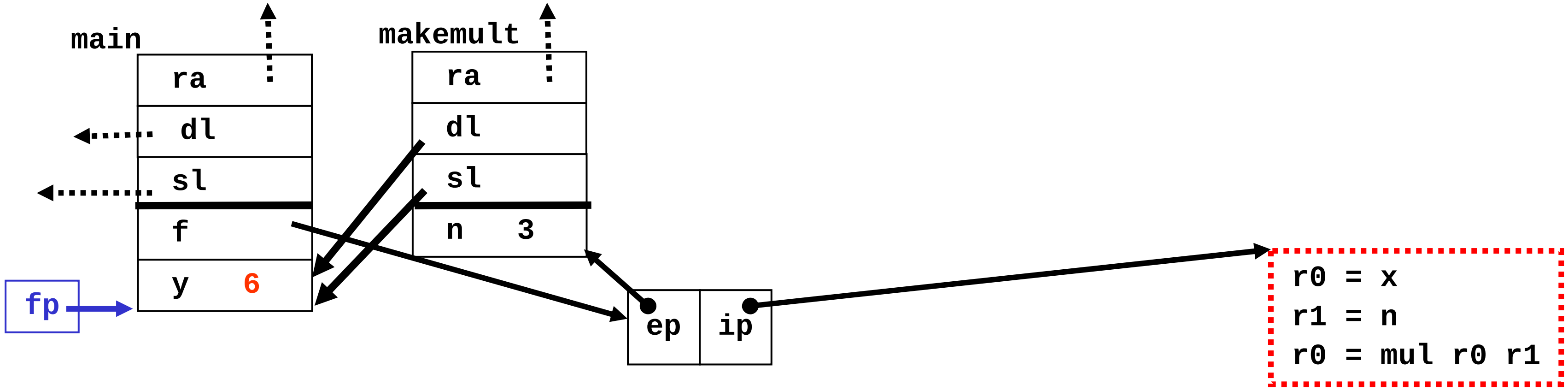
Returned Subroutines (cont.)

- After assignment **`f = . . .`**
- At prologue of call **`f(2)`**



Returned Subroutines (cont.)

- After assignment **`y = f(2)`**



- The AR for **`makemult(3)`** is never ``popped'' while **`main()`** is active
  - **`main`** activation refers to a function value **`f`**
  - functional value **`f`** requires definition of **`n`** in **`makemult`** AR
  - function **`f`** in environment can be called again many times
    - So lifetime of **`makemult`** AR is lifetime of **`main`**
- ARs now managed on a heap, along with closures