COMP 520 - Compilers

Lecture 13 (Tue Mar 29, 2022)

Run-time organization

- Reading
  - Chapter 6, section 6.1 - 6.5 (pp 173 - 229)

Where are we?

- We have completed discussion of the compiler "front-end"
  - scanning
  - parsing
  - contextual analysis
- Semantics of a program
  - defined in terms of its decorated AST
  - could be executed by an AST "interpreter"
- Next is "back end"
  - code generation
  - translate the AST semantics to operations in the target machine
- Approach
  - first try to understand the target machine
    - (lower-level) storage and execution model connects front end to back end
  - then study the translation
    - challenge: what is done at compile time and what is done at run time?

Run-time organization

- Overview of run-time issues
  - memory model and organization
  - representation of values
  - evaluation of expressions
  - procedures and functions
    - activation records
    - non-local variable access
    - parameter passing
  - runtime resources and management system

- Run-time organization for object-oriented languages
  - creation of, and access to, objects
  - inheritance and virtual methods

Target machine model

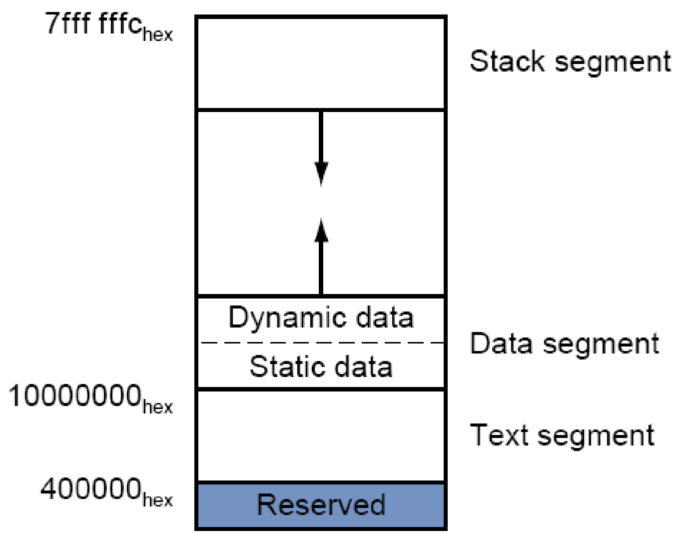
- Machine model
  - physical
    - MIPS as studied in computer organization class
    - Intel Architecture (x86-64) or ARM
  - abstract
    - Triangle Abstract Machine (TAM) from our text
    - Java Virtual Machine (JVM)

- Application Binary Interface (ABI)
  - a set of conventions
    - how values are represented (integers, floating point values, byte order)
    - where values are stored (stack, heap)
    - basic runtime facilities (memory allocation, garbage collection)
  - examples
    - MIPS
    - TAM, JVM, .NET Microsoft Common Language Runtime (CLR)

ABI: MIPS memory organization

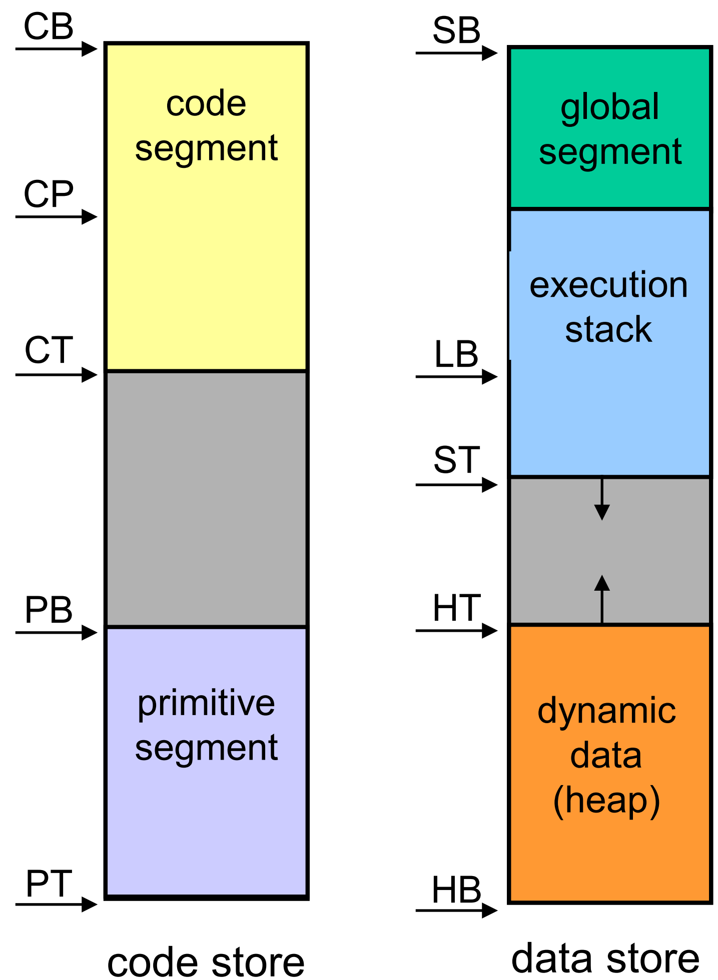
- ABI defines fixed addresses and usage conventions

- Key areas
  - "Reserved"
    - for use by operating system
  - Text segment
    - generated MIPS instructions loaded here
  - Stack segment
    - procedure invocation and expression evaluation stack
      - expands downwards
  - Data segment
    - static constants and variables are placed at the bottom
      - their locations are known by the compiler
    - dynamically-allocated data values are placed above the static data
      - e.g. new instances of a class
      - their locations cannot be predicted by the compiler (depends on run-time behavior)
      - expands upwards
      - memory for deleted (or unused) values can be reused



TAM memory organization

- Two separate memories
  - Code store
    - compiler-generated program is loaded into code segment
    - predefined runtime functions are located in the primitive segment
    - TAM can not write into code store
  - Data store
    - static constants and variables are loaded into global segment
    - procedure invocation and expression evaluation use execution stack
      - expands downwards
    - dynamically allocated values are allocated on the heap
      - expands upwards
      - memory for deleted values can be reused
- ABI defines fixed addresses and usage conventions
  - various locations in memories are accessed relative to machine registers (CB, SB, HT, etc.)



Representation of values in memory

- Values of a given type must have a well-defined representation
  - ex: double, int, char, boolean
  - typically represented as 64-bit, 32-bit, 16-bit, or 8-bit binary values
  - chosen to match underlying machine hardware
  - it is easiest for a compiler if all values of a type have the same size

- For aggregate values (records, arrays, class instances)
  - compiler must know how to access components
  - aggregate values may have static size or dynamic size
  - indirect representation of dynamic size values
    - fixed sized pointer to location of dynamic sized value

Execution model: Stack machine

- Stack machine
  - all operations take place at stack top
  - implementations
    - Burroughs 5500 (hardware interpreter)
    - TAM (software interpreter)

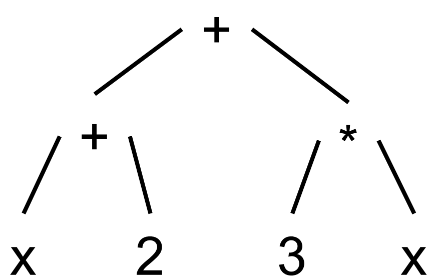
- Stack operations

STORE *addr*	pop value off stack top and store at address *addr*
LOAD *addr*	push value at address *addr* onto top of stack
LOADL *c*	push literal value *c* onto top of stack
ADD, SUB, …	perform operation at stack top: pop operands, push result
CALL *foo*	execute *foo*: *foo* receives its arguments at the stack top, consumes them, and returns its result at stack top

Code generation and execution on stack machines

- Given expression AST, construct code for expression evaluation on stack
  - via postorder traversal of AST
    - generate code for children of node (l to r) then generate code for node
    - leaf action: load value
    - non-leaf action: perform operation
- example: x + 2 + 3 * x

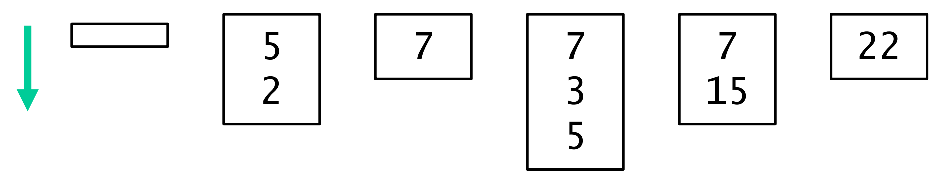
AST



Code

```
LOAD   x
LOADL  2
ADD
LOADL  3
LOAD   x
MUL
ADD
```

Execution on stack machine (x = 5)



Triangle code generation

- Triangle Abstract Machine (TAM)
  - Implements a stack machine

Triangle

```
let
   var n: Integer
   var c: Char
in
   begin
     c := '&';
     n := n + 1
   end
```

TAM instructions

```
PUSH   2        // space for n, c
LOADL  38       // ascii code '&'
STORE  1[SB]    // store in c
LOAD   0[SB]    // load n
LOADL  1
CALL   add
STORE  0[SB]    // update n
POP    2        // delete space
HALT
```

Execution model: Register machine

- Register machine
  - all operations take place in fixed collection of registers
  - implementations
    - RISC architectures, such as MIPS

- Register machine operations

STORE *r, addr*	store value in register *r* at address *addr*
LOAD *r, addr*	load value at address *addr* into register *r*
LOADL *r, c*	load literal value *c* into register *r*
ADD r3, r1, r2	r3 = r1 + r2 (r1, r2, r3 registers)
SUB r3, r1, r2	r3 = r1 – r2 (r1, r2, r3 registers)
…	

- A register machine can simulate a stack machine
  - part of Application Binary Interface (ABI),
    - e.g. a fixed register is designated as the stack pointer
  - sometimes supported in hardware (e.g. ia-32 floating point)

Expression evaluation on register machines

- Naive strategy
  - simulate stack machine
  - load values at stack top into registers for operations, and save result back onto stack

- Better strategy
  - some values can be kept in registers rather than on the stack
    - ex: x + 2 + 3 * x
    - finding optimal solution with fixed number of registers is NP-hard

```
lw   r1,x
li   r2,2
add  r1,r2,r2
li   r3,3
mul  r3,r1,r3
add  r2,r3,r1
```

Procedures and functions

- The procedure and function abstraction
  - allows us to build large programs and reuse code
  - invocation:
    - call from within a statement or expression
    - return (possibly with result) to point of call
  - local variables have separate instantiations for each invocation
    - enables recursive invocation

- Implementation of procedure and function invocation
  - a *convention*
  - machine dependent and possibly hardware assisted
  - division of responsibility between caller and callee
    - caller: set up arguments and space for result
    - callee: create space for locals, execute body, clean up space, and return
  - debuggers rely on the convention being followed

Anatomy of a function (Triangle)

function definition

function name

parameter

```
func fib(n : Integer) : Integer ~
    if n <= 2
       then 1
       else fib(n-1) + fib(n-2)
```

function body

(recursive) function call

argument

Lifetime of a function / procedure

- The *lifetime* of an activation of procedure *P* is:
  - all steps taken from the start of execution of *P* until its return to the point of call
  - includes the lifetimes of procedures that *P* calls

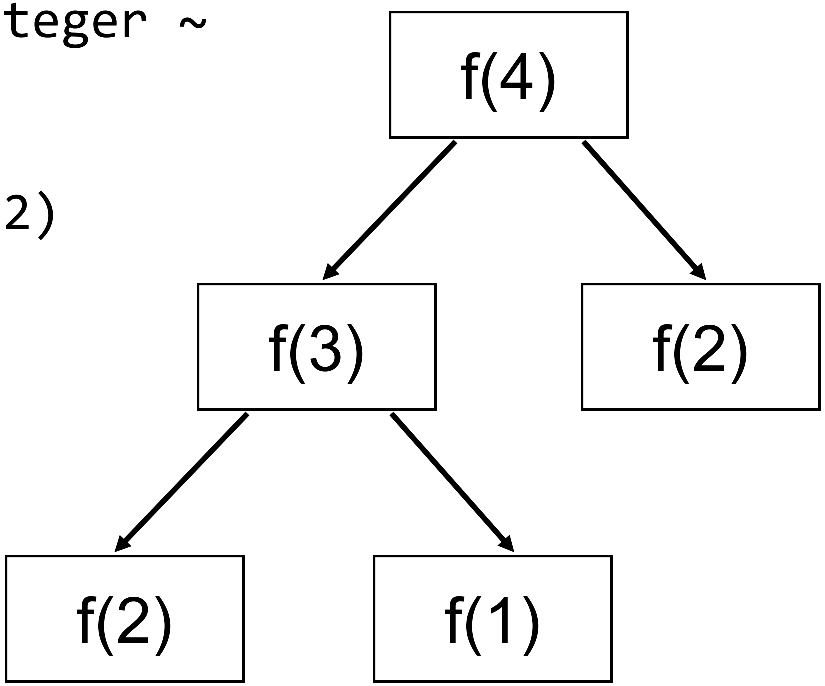
- Dynamic concept
  - may depend on parameters

- Important fact
  - Given activations of procedures A and B, their lifetimes are either disjoint or properly nested

Activation trees

Fibonacci function

```
func f (n : Integer) : Integer ~
    if n <= 2
       then 1
       else f(n-1) + f(n-2)
```



- *Depends on runtime behavior*
- *May be different for each program input*

Execution stack and activation records

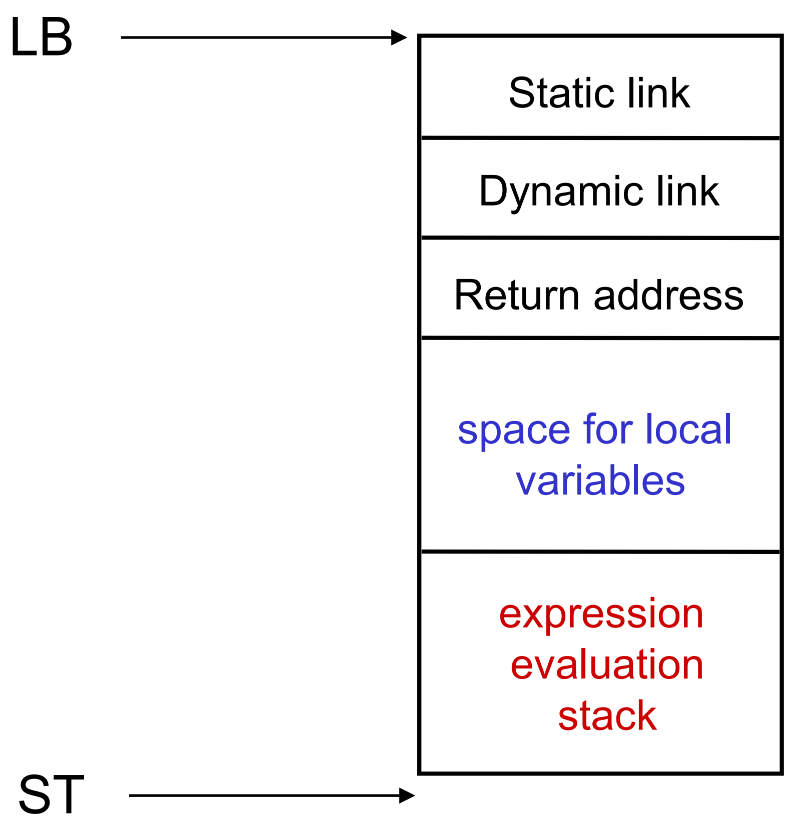
- Activation tree suggests the use of a *stack* to keep track of currently active procedures
  - superficially similar to nested scope
  - but activation tree is dynamic and scope is static

- Stack usually laid out in contiguous storage
  - each entry on the stack is a procedure or function activation record
    - Information needed to manage one procedure activation
    - <u>In our text, an activation record is known as a "frame"</u>

- If F calls G, then G's activation record contains
  - information to resume execution of F (return address)
  - arguments from F to G (often viewed as part of F)
  - local variables of G
  - result of G to F (often viewed as part of F)

Components of a frame

- Register conventions
  - the frame pointer LB (FP in MIPS) contains address of start of the frame
  - the stack pointer ST (SP in MIPS) contains address of the end of the frame and is the top of the execution stack



Dynamic link

- points at start of frame of *calling* procedure

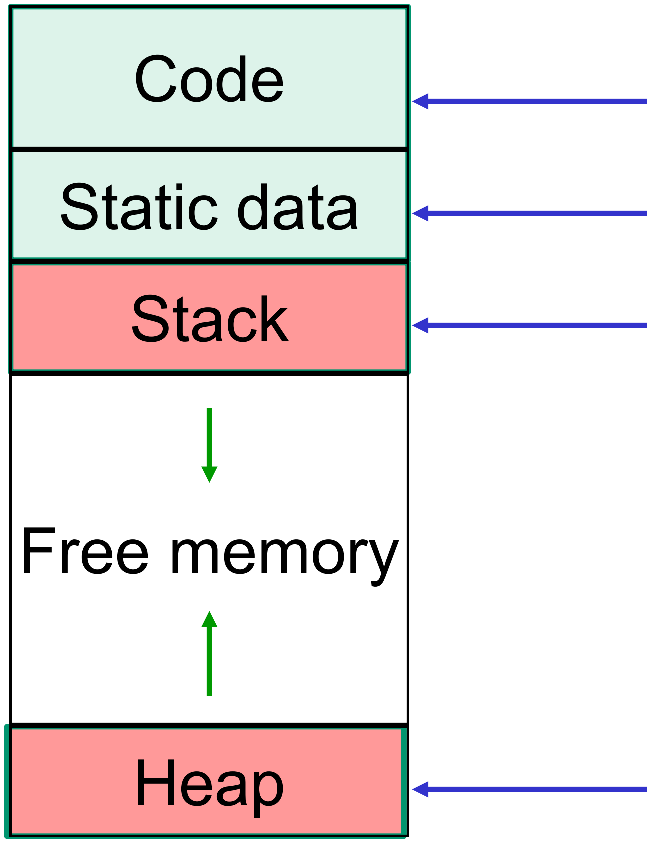
Static Link

- points at start of AR of *statically enclosing* procedure (more later)

Return address

- address to resume execution of caller

Who's Doing What and When?



Generated by compiler

Space reserved by compiler

Activation records generated at run time

Managed by run-time dynamic allocation

Recall TAM memory organization

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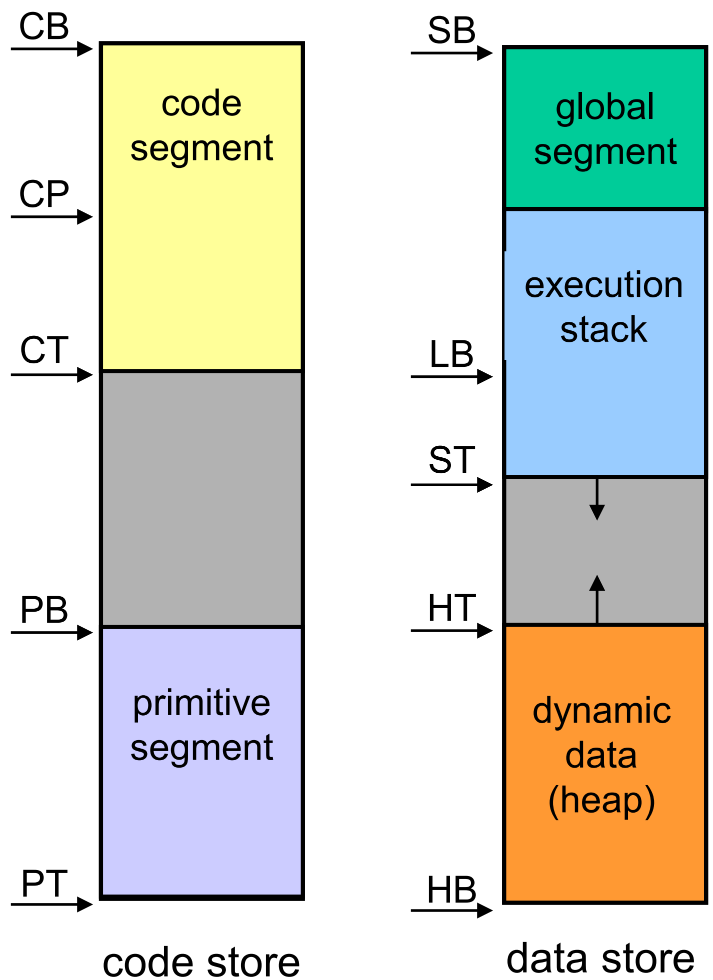


Procedures and functions

- Run-time access to variables
  - local variables
  - global variables
  - non-local, non-global variables (Triangle)
  - object instances and members (miniJava)

- Procedures and functions
  - frame maintenance
  - parameter passing
  - result value

- Heap-allocated variables
  - runtime heap management

Runtime access to local variables

- The value of a local variable may be stored
  - in an activation record on the execution stack
    - if the variable lifetime = procedure lifetime
  - in the heap
    - if the variable lifetime can exceed procedure lifetime
      - E.g. a reference returned from a procedure
- Two models of scoped variables
  - local/global scope (C)
    - all procedures (logically) declared at global scope
    - variables are declared at global scope or at local scope
    - variable references are local or global
      - where do we find the value at runtime?

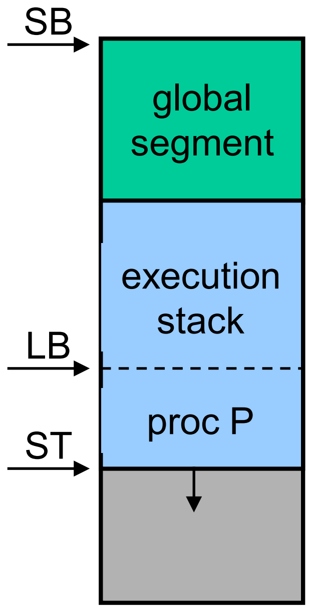
EASY!

  - nested procedures (Pascal, Triangle)
    - procedure definitions may be nested
    - variables are declared in procedures (including a special “global” procedure)
    - variable references may refer to a declaration in a surrounding procedure
      - where do we find the value at runtime?

HARD!

Local/global scope: access to variables

- A variable x can be declared
  - at global scope
    - the compiler knows $d_G(x)$, the offset of x relative to the stack base SB
    - to get the value of x at stack top in TAM
      - LOAD $d_G(x)$[SB]
    - to store value at stack top into x
      - STORE $d_G(x)$[SB]

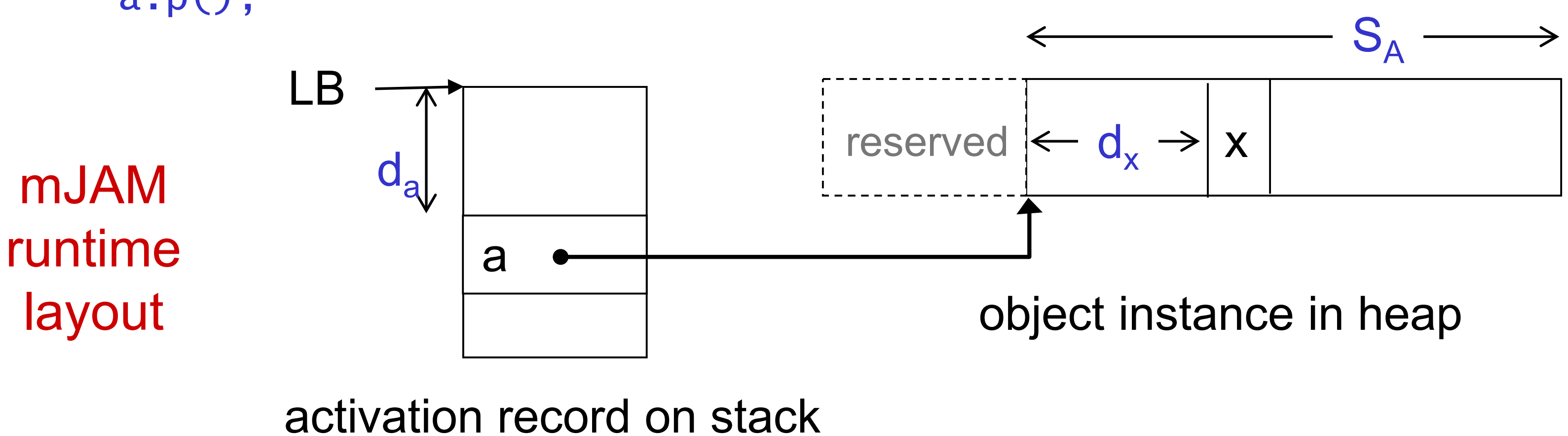


  - at local scope in procedure P
    - the variable is allocated in the frame for P and is available only while P is executing.
    - the compiler knows d(x), the offset of x relative to LB
    - to get the value of x at stack top
      - LOAD d(x)[LB]
    - to store value at stack top into x
      - STORE d(x)[LB]

Object access (preview)

- Classes
  ```
  class A {int x; void p(){x = 3;} }
  ```
  – Information known to the compiler
    - class A : S_A = size of class A (# fields)
    - field x: d_x = displacement of field x within A

- Objects
  – instances are created on the heap
  ```
  A a = new A();
  ```
  – access to members
  ```
  a.x = 2;
  a.p();
  ```



Local/gobal scope: frame maintenance

- Procedure declaration
```
int p(int x, int y) { return x+y; }
```

- Procedure call
```
int x = p(2*3, 4) + 1;
```

- Steps taken at point of call
  1. evaluate each argument expression at stack top
     - one value on the stack for each argument
  2. create new frame at stack top
     - space for dynamic link and return address (static link unused)
  3. Jump to procedure at appropriate address in instruction store

- Steps taken by the callee
  - save caller LB into dynamic link
  - save caller return address
  - set LB to start of current frame
  - execute body
  - restore LB of caller
  - restore ST of caller, popping parameters of caller and pushing result from callee
  - return to caller at RA

Nested procedures and non-local variables (Triangle)

```
let
   var a: Integer;
   proc F(b: Integer) ~
      let
         var b2: Integer;
         proc G(c: Integer) ~
            begin
               … a, b, b2, c,
              F( … ), G( … )
            end
      in
         … a, b, b2, F( … ), G( … )
in
    … a, F( … )
```

Nested procedures and non-local variables (Triangle)

level 0

```
let
   var a: Integer;
   proc F(b: Integer) ~
      let
         var b2: Integer;
         proc G(c: Integer) ~
            begin
               … a, b, b2, c,
               F( … ), G( … )
            end
      in
         … a, b, b2, F( … ), G( … )
in
   … a, F( … )
```

level 1

level 2

Nested procedures: access to non-local variables

- Procedure nesting level
  - defined as the number of enclosing procedure or function declarations at a given point in a program

- Given a reference to a variable x
  - Declaration level d_x
    - procedure nesting level at point of declaration of x
  - Reference level r_x
    - procedure nesting level at reference of x
  - $r_x \geq d_x$

- To find value of x at reference level r_x in TAM
  - assume *x* is stored at offset *h* in frame of declaring procedure

LOAD h[LB]	// if $r_x - d_x = 0$	
LOAD h[L1]	// if $r_x - d_x = 1$	L1 = LOAD 0[LB] (the static link)
LOAD h[L2]	// if $r_x - d_x = 2$	L2 = { LOAD 0[LB]; LOADI }
LOAD h[L3]	// if $r_x - d_x = 3$	L3 = { LOAD 0[LB]; LOADI; LOADI }
….	…..	…..

Nested Procedures: frame maintenance

- At procedure call
  - call P occurs at reference level r_P
  - P is declared at declaration level d_P
  - $r_P - d_P \geq 0$
- Check some examples
  - F calls F, F calls G, G calls F
  - how do we set the dynamic link? how do we set the static link?
- Steps taken by the caller
  - establish static link at start of frame (current stack top)
- Steps taken by the callee
  - save caller LB into dynamic link
  - execute body
  - restore LB of caller
  - restore ST of caller
  - pop caller arguments off stack
  - push result on the stack
  - return to caller

Parameter passing mechanisms

- Definition
  - argument
    - passed into a procedure or function
  - parameter
    - stands for something passed into a procedure or function

- Questions
  - when are arguments of function calls evaluated?
    - most languages evaluate arguments at the point of call
  - to what are the parameters bound?
    - values?
    - addresses?
    - functions?

Call-by-value

- Frequently used (e.g. C, Java)
  - ex

```
let
   proc g(x: Integer) ~  x := x + 1
   var y: Integer
in
   y := 5; g(y); print(y)
```

  - implementation
    - argument is evaluated at stacktop (= value of y) by caller
    - callee parameter x is directly before activation record of g
    - modifications to x have no effect on y, because argument is popped on return by callee

- Call-by-value-result
  - x is copied back into y on termination of g

Call-by-reference

- the address is passed instead of a value (e.g. Pascal var parameter)
  - ex

    ```
    let
        proc g(var x: Integer) ~  x := x + 1
        var y: Integer
    in
        y := 5; g(y); print(y)
    ```

  - implementation
    - argument must be a variable
    - argument is evaluated at stacktop (= address of y) by caller
    - callee parameter x is directly before activation record of g
    - a reference to x requires dereference of the pointer
    - a change to x changes y
  - why do this?
- Aliasing
  - two parameters may refer to the same location or a parameter may refer to the same location as a global variable
  - is this a problem?

Values that live on the heap

- need to be allocated and deallocated at run-time

language	allocation	deallocation
C	malloc	free
C++	new	delete
Java	new	(garbage collection)
Matlab	(implicit)	(reference counting)

- values on the heap are always passed as a reference
  – for performance reasons
  – but can lead to extensive aliasing

Run-time API

- alloc(*k*)
  – locates a block of at least *k* bytes in free space pool, removes it from pool, returns its address

- free(*p*)
  – places the block pointed to by *p* back in free space pool
  – Not needed if unused storage is automatically reclaimed

Issues in Heap Management

- Wasted space
  - If *alloc* returns blocks larger than requested, excess space is wasted
- Fragmentation
  - After a series of *alloc/free* commands, free space pool becomes fragmented, preventing allocation of large blocks
- Speed
  - *alloc* and *free* should be inexpensive