Functions

Terms

```
void foo() {
  int a, b;
  ...
  bar(a, b);
}


void bar(int x, int y) {
   ...
}
```

- foo is the *caller*
- bar is the *callee*
- a, b are the *actual parameters* to bar
- x, y are the *formal parameters* of bar
- Shorthand:
    - argument = actual parameter
    - parameter = formal parameter

Different kinds of parameters

- Value parameters
- Reference parameters
- Result parameters
- Value-result parameters
- Read-only parameters

Value parameters

- "Call-by-value"
- Used in C, Java, default in C++
- Passes the value of an argument to the function
- Makes a copy of argument when function is called
- Advantages? Disadvantages?

Advantage: if function makes modifications to its parameters, they are not seen by the caller
Disadvantage: making copies can be expensive, especially for large objects

Value parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, int z) {
   y = 2;
   z = 3;
   print(x);
}
```


Value parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?

Value parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?
- Answer:

  print(x); //prints 1

  print(x); //prints 1

Reference parameters

- "Call-by-reference"
- Optional in Pascal (use "var" keyword) and C++ (use "&")
- Pass the *address* of the argument to the function
- If an argument is an expression, evaluate it, place it in memory and then pass the address of the memory location
- Advantages? Disadvantages?

Advantages: much faster -- no need to copy arguments
Disadvantages: (i) programmer must be careful: if callee modifies arguments, caller sees it. (ii) allows for aliasing

Reference parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int &y, int &z) {
   y = 2;
   z = 3;
   print(x);
}
```


Reference parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int &y, int &z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?

Reference parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int &y, int &z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?
- Answer:

  print(x); //prints 3

  print(x); //prints 3

Result parameters

- Return values of a function
  - Some languages let you specify other parameters as result parameters – these are un-initialized at the beginning of the function
- Copied at the end of function into the arguments of the caller
  - C++ supports "return references"

    `int& foo( ... )`

    compute return values, store in memory, return address of return value

Result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, result int z) {
   y = 2;
   z = 3;
   print(x);
}
```


Result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?

Result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y, result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?
- Answer:

  print(x); //prints 3

  print(x); //prints 1

Value-result parameters

- "Copy-in copy-out"
- Evaluate argument expression, copy to parameters
- After subroutine is done, copy values of parameters back into arguments
- Results are often similar to pass-by-reference, but there are some subtle situations where they are different

Value-result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```


Value-result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?

Value-result parameters

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?
- Answer:

  print(x); //prints 3

  print(x); //prints 1

What about this?

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(value result int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```


What about this?

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(value result int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?

What about this?

```
int x = 1;
void main () {
   foo(x, x);
   print(x);
}

void foo(value result int y,
    value result int z) {
   y = 2;
   z = 3;
   print(x);
}
```

- What do the print statements print?
- Answer:

  print(x); //undefined!

  print(x); //prints 1

Read only parameters

- Used when callee will not change value of parameters
- Read-only restriction must be enforced by compiler
- This becomes tricky when in the presence of aliasing and control flow

```
void foo(readonly int x, int y) {
  int * p;
  if (...) p = &x else p = &y
  *p = 4
}
```

- Is this legal? Hard to tell!

Esoteric: "name" parameters

```
int x = 2;
void main () {
   foo(x + 2);
}

void foo(int y) {
   z = y + 2;
   print(z);
}
```

Esoteric: "name" parameters

- "Call-by-name"
  - Usually, we evaluate the arguments before passing them to the function. In call-by-name, the arguments are passed to the function before evaluation
  - Not used in many languages, but Haskell uses a variant

```
int x = 2;
void main () {
   foo(x + 2);
}

void foo(int y) {
   z = y + 2;
   print(z);
}
```

⟶

```
int x = 2;
void main () {
   foo(x + 2);
}

void foo(int y) {
   z = x + 2 + 2;
   print(z);
}
```


Why is this useful?

```
int x = 2;
void main () {
   foo(bar());
}

void foo(int y) {
   z = 3;
   print(z);
}
```

- Consider the code on the left
- Normally, we must evaluate bar() before calling foo()
- But what if bar() has an infinite loop?
- In call by name, this program still terminates

Other considerations

- Scalars
  - For call by value, can pass the address of the actual parameter and copy the value into local storage within the procedure
    - Reduces size of caller code (why is this good?)
  - If scalar is a constrained type (*e.g.*, a Pascal range type), must insert type check for return values
  - For machines with a lot of registers (*e.g.*, MIPS), compilers will save a few registers for arguments and return types
    - Less need to manipulate stack

Why is this good? Because there is one function definition and many calls. Saving code at each call site makes the code smaller.

Other considerations

- Arrays
  - For efficiency reasons, arrays should be passed by reference (why?)
    - Java, C, C++ pass arrays by reference by default (technically, they pass a pointer to the array by value)
  - Pass in a fixed size dope vector as the actual parameter (not the whole array!)
  - Callee can copy array into local storage as needed

why: because arrays are large!

Dope vectors

- Remember: store additional information about an array
  - Where it is in memory
  - Size of array
  - # of dimensions
  - Storage order
- Can sometimes eliminate dope vectors with compile-time analysis

Strings

- Requires a descriptor
  - Like a dope vector, provides information about string
- May just need to pass a pointer (if string contains information about its length)
- May also need to pass information about length

Calling a function

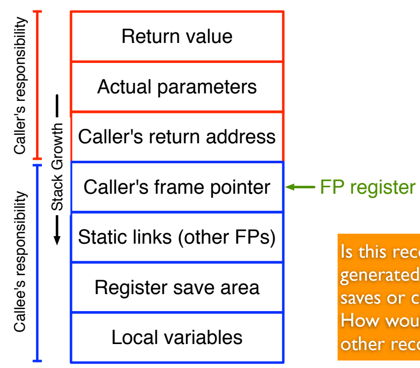
- What should happen when a function is called?
  - Set the frame pointer (sets the base of the activation record)
  - Allocate space for local variables (use the function's symbol table for this)
  - What about registers?
    - Callee might want to use registers that the caller is using

Saving registers

- Two options: caller saves and callee saves
- Caller saves
  - Caller pushes all the registers it is using on to the stack before calling function, restores the registers after the function returns
- Callee saves
  - Callee pushes all the registers it is *going to use* on the stack immediately after being called, restores the registers just before it returns
- Why use one vs. the other?
- Simple optimizations are good here: don't save registers if the caller/callee doesn't use any

Caller saves: ensures that any variables that are register allocated can be seen by the callee; makes exception handling/multiple return points easy (just return from callee -- no need to restore registers)

Activation records



Is this record generated for callee-saves or caller-saves? How would the other record look?

Callee saves (you can tell because the callee is responsible for the registers). For caller saves, the registers would be stored with the caller's return address

The frame pointer

- Manipulate with instructions like `link` and `unlink`
  - Link: push current value of FP on to stack, set FP to top of stack
  - Unlink: read value at current address pointed to by FP, set FP to point to that value
  - In other words: link pushes a new frame onto the stack, unlink pops it off

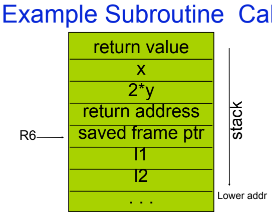
Example Subroutine Call and Stack Frame

Lower addr

```
z = SubOne(x,2*y);
```

```
int SubOne(int a, int b) {
    int l1, l2;
    l1 = a;
    l2 = b;
    return l1+l2;
};
```


Example Subroutine Call and Stack Frame




```
z = SubOne(x,2*y);
```

```
int SubOne(int a, int b) {
    int l1, l2;
    l1 = a;
    l2 = b;
    return l1+l2;
};
```

Example Subroutine Call and Stack Frame

Stack
return value
x
2*y
return address
saved frame ptr
l1
l2
. . .

R6 (points to: saved frame ptr)

stack

Lower addr

3-address code:

```
push
push x
mul 2 y t1
push t1
jsr SubOne
pop
pop
pop z
```

```
link 3
move $P1 $L1
move $P2 $L2
add $L1 $L2 t2
move t2 $R
unlink
ret
```

```
z = SubOne(x,2*y);
```

```
int SubOne(int a, int b) {
    int l1, l2;
    l1 = a;
    l2 = b;
    return l1+l2;
};
```


Example Subroutine Call and Stack Frame

Stack
return value
x
2*y
return address
saved frame ptr
l1
l2
. . .

R6 (points to: saved frame ptr)

stack

Lower addr

3-address code:

```
push
push x
mul 2 y t1
push t1
jsr SubOne
pop
pop
pop z
```

```
link 3
move $P1 $L1
move $P2 $L2
add $L1 $L2 t2
move t2 $R
unlink
ret
```

assembly code:

```
push
push x
load y R1
muli 2 R1
push R1
jsr SubOne
pop
pop
pop R1
store R1 z
```

```
link R6 3
load 3(R6) R1
store R1 -1(R6)
load 2(R6) R2
store R2 -2(R6)
load -1(R6) R1
add -2(R6) R1
store R1 4(R6)
unlink
ret
```

```
z = SubOne(x,2*y);
```

```
int SubOne(int a, int b) {
    int l1, l2;
    l1 = a;
    l2 = b;
    return l1+l2;
};
```


Example2

Stack
return value
&x
&y
return address
saved frame ptr
l1
l2
b.f100
…
b.f2
b.f1

R6 (points to: saved frame ptr)

stack

3-address code:

```
push
push &x
push &y
jsr SubOne
pop
pop
pop z
```

```
link 103
blkmv $(P2) $L3 100
move $(P1) $L1
move $L3%4 $L2
add $L1 $L2 t2
move t2 $R
unlink
ret
```

assembly code:

```
push
push &x
push &y
jsr SubOne
pop
pop
pop R1
store R1 z
```

```
link R6 103
load 2(R6) R1
load &-102(R6) R2
blkmv R1 R2 100
load 3(R6) R1
load (R1) R2
store R2 -1(R6)
load -99(R6) R1
store R1 -2(R6)
load -1(R6) R1
add -2(R6) R1
store R1 4(R6)
unlink
ret
```

```
z = SubOne(x,objy);
```

```
int SubOne(int & a, Class1 b) {
    int l1, l2;
    l1 = a;
    l2 = b.f4;
    return l1+l2;
};
```