Subprograms

Programming Languages

CS 214

Categorizing Functions

Recall: The *function* set constructor: *f(D)* →*R*
can be used to describe the operations in a language.

This approach categorizes functions domain (D) and range (R)

Example: C++ lets us use function notation to *cast*…

```
int( real )  → int
double( int )  → real
```

But if we write a *round()* function:

```
int round( double value) { return int(value + 0.5); }
```

then *round()* is also a member of: `(real) → int`

and *int()* and *round()* obviously *behave* very differently...

Functions: as *Mapping Rules*

The function constructor defines a function's *specification* (i.e., it's domain- and range-sets), but not its *behavior* (i.e., indicate the domain-to-range element mappings).

Behavior can be defined via a *domain-to-range mapping rule*:

Example: In C++, we can *specify* that: $abs(\ int\ ) \rightarrow int$

but to define the *behavior* of *abs()*, we need a rule:

$$abs(v) = \begin{cases} \{v, \text{ if } v >= 0; \\ -v \text{ otherwise } \} \end{cases}$$

A *mapping rule* must specify the range-value for each domain-value for which the function is defined.

Functions: as *Algorithms*

An alternative way to specify behavior is to specify:

- the function's *name*
- the function's *parameters*
- a *rule* for computing the result, using the parameters.

```
-- Ada
function abs(val: in float)
         return float is
begin
  if val >= 0.0 then
    return val;
  else
    return -val;
  end if;
end abs;
```

```
"Lisp"
(defun abs (val)
  (if (>= val 0)
    val
    (- 0 val) ))
```

```
"Smalltalk (Number method)"
abs
  self >= 0
    ifTrue: ^self
    ifFalse: ^(0 - self).
```

Some like to view a HLL as a syntax for writing algorithms.

Functions and Operators

Most *functions* can be defined as *operators*, and vice versa.

Example: Ada provides an exponentiation operator **
where C++ provides an exponentiation function *pow()*.

So a 3rd-order polynomial can be expressed in C++ as

```
y = a * pow(x,3) + b * pow(x,2) + c * x + d;
```

or in Ada as:

```
y = a * x ** 3 + b * x ** 2 + c * x + d;
```

Superficially, functions and operators are *equivalent*:

- The *arguments* of a function ≡ the *operands* of an operator.
- A *function* can be thought of as a *prefix operator*.

Functions: as *Abstractions*

Others prefer to view functions as an *abstraction mechanism*:
- the ability to hide algorithm details behind a name...

Example: If a library provides a *summation()* function, it might use any of these algorithms:

```
// iterative algorithm
int summation(int n) {
  int result = 1;
  for (int i = 2; i <= n; i++)
    result += i;
  return result;
}
```

```
// recursive algorithm
int summation(int n) {
  if (n >= 2)
    return n + summation(n-1);
  else
    return 1;
}
```

```
// using Gauss' formula
int summation(int n) {
  return n * (n+1) / 2;
}
```

The name *summation()* is an *abstraction* that hides the details of the particular algorithm it uses.

Functions: as *Subprograms*

Imperative HLLs divide functions into two categories:

- *Procedures*: subprograms that map: $(P_1 \cdot P_2 \cdot \ldots \cdot P_n) \rightarrow \emptyset$
- *Functions*: subprograms that map: $(P_1 \cdot P_2 \cdot \ldots \cdot P_n) \rightarrow R \neq \emptyset$

There are no standard names for these categories:

HLL	$(D) \rightarrow \emptyset$	$(D) \rightarrow R$
C/C++	void function	function
Fortran	subroutine	function
Pascal	procedure	function
Modula-2	proper procedure	function procedure
Ada	procedure	function

We will describe subprograms mapping $(D) \rightarrow R$ as *functions*, and describe subprograms mapping $(D) \rightarrow \emptyset$ as *procedures*.

Functions: as *Messages*

OO languages view functions as *messages to objects*.

The *receiver* of a message executes its *corresponding method*.

– The result is controlled by the *receiver*, not the *sender*.

Different OO languages use different syntax for messages...

Example: To find the length of *anArray*, we send it a message:

```
// C++
anArray->length()
```

```
// Java
anArray.length
```

```
// Smalltalk
anArray size
```

Example: To find the length of *aString*, we send it a message:

```
// C++
aString->length()
```

```
// Java
aString.length()
```

```
// Smalltalk
aString size
```

Messages are something like postfix operations...

Subprogram Mechanisms

To have a subprogram mechanism, a language must provide:

- A means of *defining* the subprogram (specifying its *behavior*);
- A means of *calling* the subprogram (or *activating* it).

In programming languages, to *define* a thing is to:

- Allocate storage for that thing; and
- Bind the thing's name to the address of that storage.

Example: This is a C++ subprogram *definition*: because it:

```
int summation(int n) {
  return n * (n+1) / 2;
}
```

(i) reserves storage (for the function's code); and

(ii) binds the name *summation* to the first address in that storage.

Definitions vs. Declarations

Where a *definition* binds a name to *storage*,
a *declaration* binds a name to a *type-constructor*.

Example: This is a C++ *declaration*:

```
int summation(int n);
```

because it tells the compiler this about *summation*:

$$summation(int) \rightarrow int$$

allowing the compiler to type-check calls to the function.

For a *variable*, declaration and definition are *the same*...

```
int result;
```

This statement reserves a word of memory, and binds the name *result* to the address of that word.

For *subprograms*, declaration and definition can be separated.

C/C++ Function Pointers

Implication of a function *definition*:

a C/C++ function's name is a *pointer to the starting address of that function.*

Example: If *summation* and *factorial* are two functions:

```
int summation(int n) { return n * (n+1) / 2; }
int factorial(int n) { … definition of factorial … }
```

then we can *declare a pointer type*:

```
typedef int * fptr(int);
```

use it to *define a pointer array*:

```
fptr fTable[2];
```

initialize our array:

```
fTable[0] = summation;
fTable[1] = factorial;
```

and then *call either function*:

```
cout << fTable[i](n);
```

Classes use a similar table for *virtual/polymorphic functions*.

Subprogram Definitions

To allocate a subprogram's storage, 4 items are needed:

1. Its parameters (*data* storage for values sent by the caller);
2. Its *return-type* (*data* storage for the return value);
3. Its *locals* (*data* storage for local variables); and
4. Its *body* or statements (*executable code* storage).

These are all provided by a subprogram's *definition*.

By contrast, a subprogram's *declaration* requires only:

1. Its parameter's types (i.e., its domain-set *D*); and
2. Its return type (i.e., its range-set *R*)

This *function signature*: $f(D) \rightarrow R$

lets the compiler check *calls* to the function for correctness.

Imperative Examples

Consider these imperative function definitions:

```
// C++
void swap(int & a, int & b) {
  int t = a; a = b; b = t;
}
```

```
-- Ada
procedure swap(a, b: in out integer) is
integer t;
begin
  t := a; a := b; b := t;
end swap;
```

In each case, we have: **`swap( int& x int& ) → null`**

This allows the compiler to check that in calls: swap(*x*, *y*); the arguments *x* and *y* are compatible with the parameters.

Subprograms: Lisp and Smalltalk

A Lisp subprogram definition uses the *defun* function:

```
"Lisp"
(defun factorial (n)
  if (< n 2)
    1
    (* n (factorial (- n 1) )) )
```

When evaluated, *defun* parses the function that follows it and (assuming no errors) creates a symbol table entry for it.

A Smalltalk subprogram must be a member of a class:

```
"Smalltalk Integer method"
factorial
  | result |
  result := 1.
  2 to: self
    do: [:i | result:= result * i].
  ^result
```

On an *accept event*, Smalltalk parses the method and (assuming no errors) creates a symbol table entry for it.

Calling Subprograms

In most languages, a subprogram is called by *naming it*.

```
// C++
swap(x, y);
```

```
-- Ada
swap(x, y);
```

```
(* Modula-2 *)
swap(x, y);
```

```
* Fortran
  CALL swap(x, y);
```

Fortran subroutines must be called with the *CALL* keyword.

Lisp functions must be called As a valid expression (following an o-parenthesis):

```
"Lisp"
(setq answer (factorial n) )
```

Smalltalk requires that a message be sent to an object:

```
"Smalltalk"
answer := 5 factorial
```

Issue: Parameterless Subprograms

Must parentheses be given at calls to parameterless functions?

- C/C++: *yes*

```
doSomething();
```

() is the *function-call operator;* jumps to address preceding it

- Ada: *no*

```
doSomething;
```

() delimits arguments (syntax)

- Modula-2: *no*

```
doSomething;
```

() delimits arguments

- Fortran: *no*

```
CALL doSomething
```

() delimits arguments

- Lisp: *yes, but...*

```
(doSomething)
```

() delimits function calls

- Smalltalk: *no, but...*

```
obj doSomething
```

no method has 0 parameters...

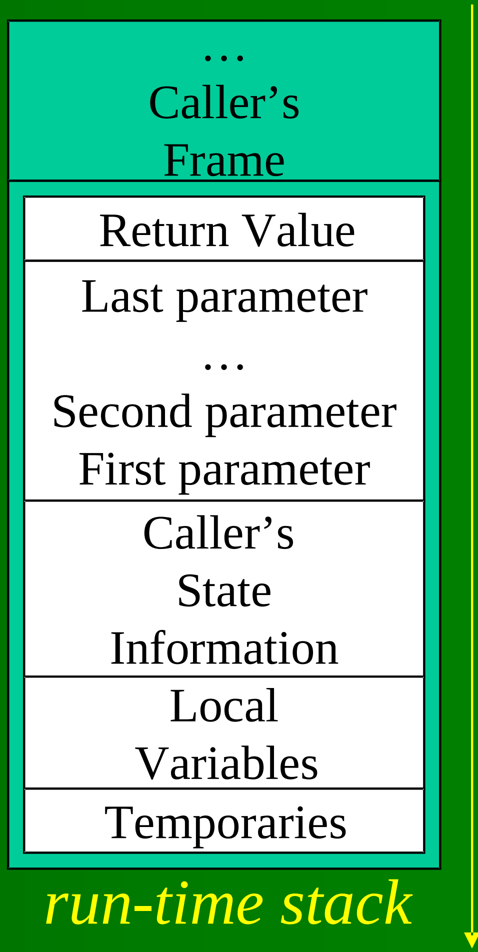
Activations

An *activation* is a call to a subprogram, and involves 3 steps:

- Space for the subprogram's data values is allocated on a special *run-time stack*;
- The caller's arguments are associated with the subprogram's parameters;
- Control is transferred from the caller to the starting address of the subprogram.

On Unix systems, the run-time stack grows "downward"

The space for one subprogram's data is called a *stack frame*, or *activation record*.



Why a Stack?

Consider a *recursive* subprogram:

When called: *sum(3)*

sum(3) calls: *sum(2)*

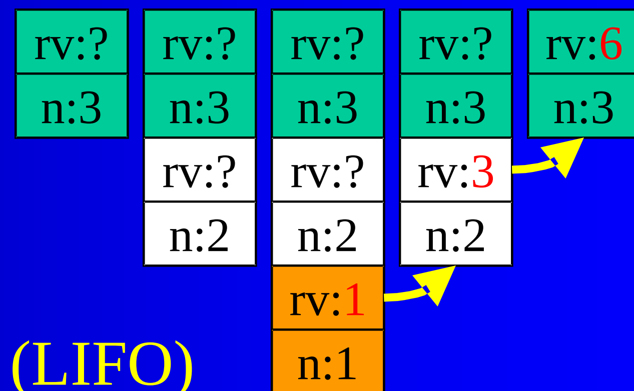
sum(2) calls: *sum(1)*

sum(1) returns 1 to: *sum(2)*

sum(2) returns 2+1 to: *sum(3)*

sum(3) returns 3+3 to its caller.

```
// C++
int sum(n) {
 if (n > 1)
  return n + sum(n-1);
 else
  return 1;
}
```



The call-sequence uses Last In First Out (LIFO) behavior, so a *stack* is the appropriate data structure.

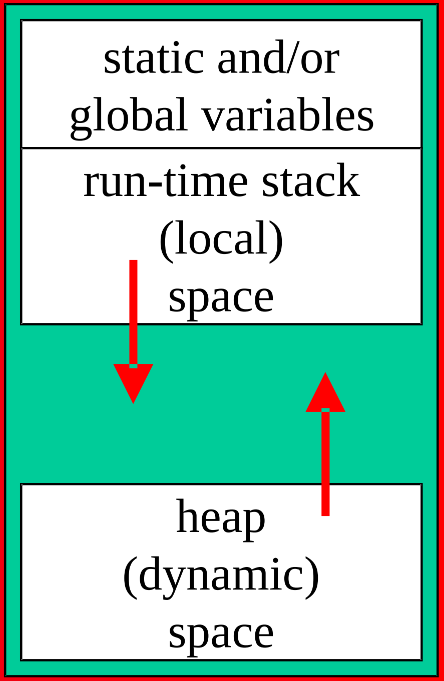
Each activation's parameters (*n*) and locals must be kept distinct.

A stack is necessary in *any language that supports recursion*.

Memory Layout

On Unix systems, a program's data space is laid out something like this:

- Space for *static/global variables*
- The *run-time stack* for locals, parameters, etc.
- The *heap* for dynamically allocated variables.



This flexible design uses memory efficiently: A typical program only runs out of memory if

- its *stack overruns its heap* (*runaway recursion*), or
- its *heap overruns its stack* (*memory leaks*).

Parameter Passing

Return Value
Last parameter … Second parameter First parameter
Caller's State Information
Local Variables
Temporaries

Parameters are allocated space within the subprogram's activation record on the run-time stack.

Before control is transferred to the subprogram, the call's arguments are "associated with" these parameters.

Exactly how arguments get associated with parameters depends on the *parameter passing mechanism* being used.

There are *four* general mechanisms: call-by…

value *reference* *copy-restore* *name*

Call-by-Value Parameters

… are value into which their arguments are *copied*. – Changing a parameter doesn't affect its argument's value.

- This is the *default* mechanism in most languages.
- This is the *only* mechanism in C, Lisp, Java, Smalltalk, ...

```
// C++
int summ (int a, int b) {
  return (a+b) * (b-a+1) / 2;
}
```

```
-- Ada
function summ (a, b: in integer)
          return integer is
begin
  return (a+b) * (b-a+1) / 2;
end summ;
```

```
"Lisp"
(defun summ (a b)
 (/ (* (+ a b) (+ (- b a) 1))
    2) )
```

```
"Smalltalk Integer method"
summ: b
   ^(self+b) * (b-self+1) / 2
```

In Ada, *in* is optional, but is considered good programming style.

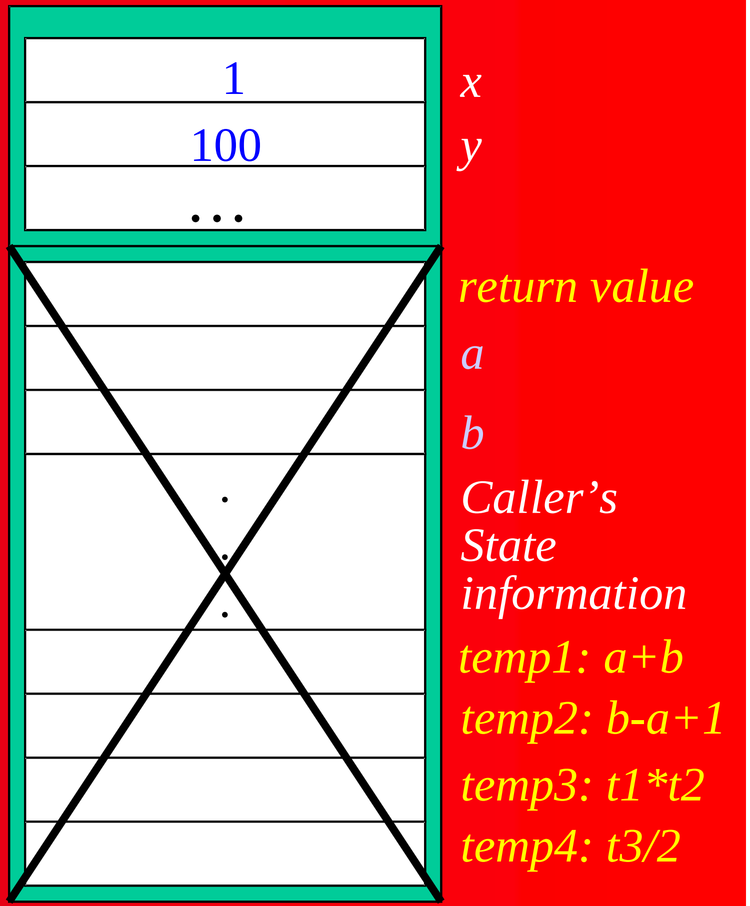
When function *summ()* is called

```
// C++
total = summ(x, y);
```

– An activation record for *summ()* containing space for *a* and *b* is pushed onto the run-time stack.

– The arguments are evaluated and copied into their parameters.

– Control is tranferred to *summ()* which executes and computes its return-value.



– *summ()*'s AR is popped, and control returns to the caller which retrieves the return-value from just "above" its stack-frame.

Call-by-Reference Parameters

… are pointers storing *the addresses of their arguments*, that are auto-dereferenced whenever they are accessed.

- The parameter is an *alias* for the argument.
- Changing the parameter's value changes the argument's value.

```
// C++
void swap (int& a, int& b) {
  int t = a; a = b; b = t;
}
```

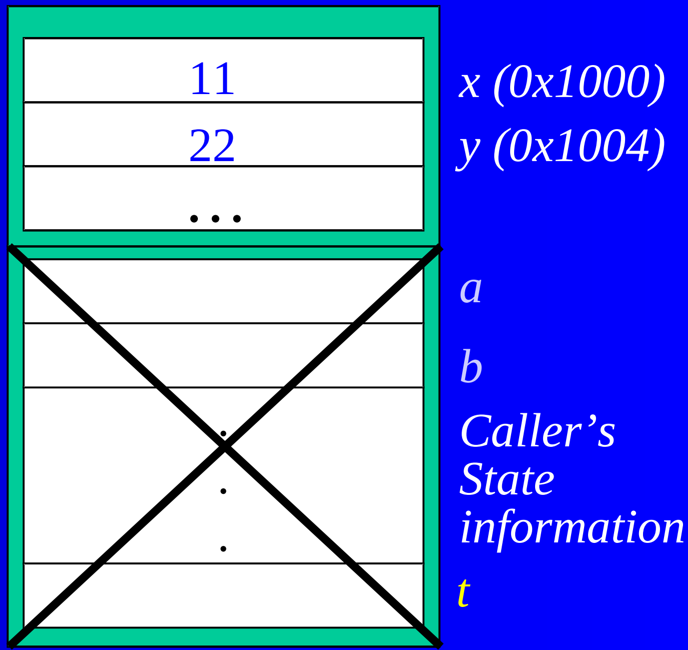
```
-- Ada
procedure swap (a, b: in out integer)
is  t: integer;
begin
  t:= a; a:= b; b:= t;
end swap;
```

Smalltalk and Lisp *implicitly* provide call-by-reference, because "variables" are actually pointers to dynamic objects.

Java is complicated...

When *swap()* is called

```
// C++
swap(x, y);
```



- An activation record for *swap()* containing space for *a* and *b* is pushed onto the run-time stack.
- The *addresses* of the arguments are stored into their parameters.
- Control is transferred to *swap()* which executes, automatically dereferencing accesses to *a* and *b*.
- The RTS is popped, control returns to the caller, and the original values of *x* and *y* have been overwritten with new values.

Implementing Call-by-Reference?

Stroustrup's first C++ "compiler" just produced C code, so if C only provides the call-by-value mechanism, how can it handle the C++ call-by-reference mechanism?

```
// C++
swap(x, y);
```

1. At the call, replace arguments with their ***adresses***:

```
/* C */
swap(&x, &y);
```

```
// C++
void swap (int& a,
           int& b);
```

2. In the declaration and definition, replace reference parameters with ***pointers***:

```
/* C */
void swap (int* a,
           int* b);
```

```
// C++
void swap (int& a,
           int& b)
{  int t = a;
   a = b;
   b = t;
}
```

3. Within the function definition, *dereference* each access to the parameter

```
/* C */
void swap (int* a,
           int* b)
{  int t = *a;
   *a = *b;
   *b = t;
}
```

Any compiler can implement call-by-reference this way.

Call-by-Copy-Restore Parameters

… store *both the value and the address of their arguments*.

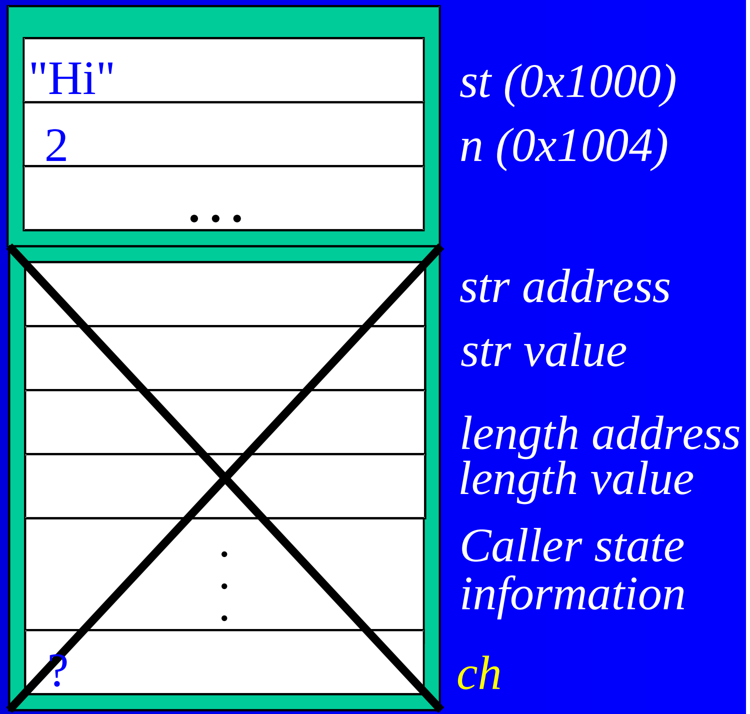
- Within the subprogram, parameter accesses use the local value
- When the subprogram terminates, the local value is *copied back* into the corresponding argument.
- More time-efficient then call-by-reference for *heavily-used parameters* (avoids slow pointer-dereferencing).
- Ada's *in-out* parameters *may* use copy-restore...

```
procedure get (str: in out ubString; length in out integer) is
  ch: character;
begin
  length:= 0; str:= ""; get(ch);
  while not End_Of_Line loop
     str:= str + ch;
     length:= length + 1;
     get(ch);
end get;
```

When *get()* is called

```
-- Ada
get(st, n);
```

- An activation record for *get()* containing space for the *data and address* of both *str* and *length* is pushed onto the run-time stack.
- Argument *values and addresses* are written to their parameters.
- Control is tranferred to *get()* which executes, accessing only local values *str* and *length*.
- The original values of arguments *st* and *n* are overwritten with the values of parameters *str* and *length*, the RTS is popped, and control returns to the caller.



Aliasing

Copy-restore parameters behave the same as reference parameters, so long as the parameter is not an *alias* for a non-local that is accessed within the same subprogram.

Example:
Suppose we have this subprogram:

```
procedure aliasExample (param: in out integer) is
begin
  param:= 1;
  a:= 2;
end get;
```

and we execute:

```
a:= 0;
aliasExample(a);
put(a);
```

What is output, if *param* uses:

- call-by-*reference*?

- call-by-*value-restore*?

To avoid this, Ada *forbids aliasing*.

Call-by-Name Parameters

1. *Copy the body* of the subprogram;
2. In the copy, *substitute the arguments for the parameters*;
3. *Substitute the resulting copy for the call*;

The result is the *call-by-name* mechanism (aka *macro-substitution*).

```
/* C */
#define SWAP (a, b) { int t = a; a = b; b = t; }
```

```
// C++
inline void swap (int& a, int& b) { int t = a; a = b; b = t; }
```

– Call-by-name originated with *Algol-60*.

– By replacing the function-call with the altered body, call-by-name:

improves time efficiency by eliminating the call and the RTS overhead; but

decreases space-efficiency by increasing the size of the program.

At each call to *swap()*

```
// C++ call to swap()
swap(w, x);
```

```
// C++ call to swap()
swap(y, z);
```

- The compiler makes a *copy* of the body of the function.

```
{ int t = a; a = b; b = t; }
```

```
{ int t = a; a = b; b = t; }
```

- In it, the compiler *substitutes arguments for parameters*.

```
{ int t = w; w = x; x = t; }
```

```
{ int t = y; y = z; z = t; }
```

- The compiler *substitutes the resulting body for the call*.

```
// C++ call to swap()
{ int t = w; w = x; x = t; }
```

```
// C++ call to swap()
{ int t = y; y = z; z = t; }
```

The resulting code is *larger*, but without the overhead of pushing a stack-frame, setting parameters, … it runs *faster*.

Macro-Substitution Anomaly

Suppose we have defined this C macro:

```
#define SWAP (a, b) { int t = a; a = b; b = t; }
```

a and *i* are as follows: *i* [2] *a* [11 | 22 | 33 | 44 | 55]

and we call: *SWAP(i, a[i]);*

What we expect is: *i* [ ] *a* [11 | 22 | | 44 | 55]

but what we get is: *bus error: core dumped*

What happened? Our call: *SWAP(i, a[i]);*

is replaced by: *{int t = i; i = a[i]; a[i] = t; }*

Tracing, we see: *t* [ ] *i* [ ] *a[i]* → *a[33]* → bus error

Because of such unexpected results, the use of macro-substitution (#define) for call-by-name is discouraged.

What About *inline*?

Suppose we have defined this C++ *inline* function:

```
inline void swap (int& a, int& b) { int t = a; a = b; b = t; }
```

a and *i* are as follows: *i*

i		a				
2		11	22	33	44	55

and we call: `swap(i, a[i]);`

What we expect is:

i		a				
33		11	22	2	44	55

and we get:

i		a				
		11	22		44	55

What happened? Our call: `swap(i, a[i]);`

is replaced by:

```
{int* t1 = &i; int* t2 = &a[i];
 int t = *t1; *t1 = *t2; *t2 = t;}
```

Since *a[i]* has a reference parameter, its address is computed and stored (in *t2*), and changes to i do not affect t2.

Call-by-name (via inline) is *safe* in C++.

Summary

There are two broad categories of subprograms:

- *procedures*: that map: $(P_1 \cdot \ P_2 \cdot \ \ldots \cdot \ P_n) \rightarrow$ null/void
- *functions*: that map: $(P_1 \cdot \ P_2 \cdot \ \ldots \cdot \ P_n) \rightarrow$ null/void

When a subprogram is *called*, an *activation record* containing space for its variables is pushed onto the *runtime stack*.

The four parameter-passing mechanisms are: Call-by - value stores a copy of the argument.

- Value stores the address (reference) of the argument and auto-dereferences all accesses to the parameter.
- Reference stores a copy and the address of the argument, and replaces the argument's value with the copy's value on termination.
- Name makes a copy of the function, replaces the parameter in the copy with the argument, and then replaces the call with that copy.

