SUBROUTINES AND CONTROL ABSTRACTION

PRINCIPLES OF PROGRAMMING LANGUAGES

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Programming is about building abstractions.

Subroutines are the main method to build control abstractions.

The other form of abstraction we normally think about is data abstraction (next topic).
ROAD MAP

• Functions, procedures, and parameters
• Inline expansion
• Parameter passing modes
• Passing functions as arguments
• Default and named parameters
• Variadic subroutines
• Generic subroutines
• Exception handling
• Continuations
• Coroutines
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**Subroutine**

- **Function** if it returns a value
- **Procedure** if it does not and thus is called for its side effects
**BASIC DEFINITIONS**

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The parameter names that appear in the subroutine declaration
## Basic Definitions

### Subroutine

- **Function** if it returns a value
- **Procedure** if it does not and thus is called for its side effects

### Formal Parameters of a Subroutine

The parameter names that appear in the subroutine declaration.

### Actual Parameters or Arguments of a Subroutine

The values bound to the formal parameters when the subroutine is called.
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- **Procedure** if it does not and thus is called for its side effects

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The parameter names that appear in the subroutine declaration

**Actual parameters or arguments of a subroutine**

The values bound to the formal parameters when the subroutine is called

We already discussed **activation records** or **(stack) frames** as a means to manage the space for local variables allocated to each subroutine call.
STATIC CHAINS AND DYNAMIC CHAINS

Source code:

A
B
  C
  Call D
E
  Call B
  Call E

Program execution:

Enter A
Call E
Enter E
Call B
Enter B
Call D
Enter D
Call C
Enter C

Execution stack:

C
D
B
E
A

Dynamic chain
Static chain
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Advantages:

- Avoids overhead associated with subroutine calls; faster code.
- Encourages building abstractions in the form of many small subroutines.
- Related to but cleaner than macros.
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• Encourages building abstractions in the form of many small subroutines.
• Related to but cleaner than macros.

Disadvantages:

• Code bloating
• Cannot be used for recursive subroutines.
• Code profiling becomes more difficult.
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PARAMETER PASSING

Notation:

\[ f(a, b, c) \]  
\[ (f\ a\ b\ c) \]  
\[ a\ f: \ b\ f\cont: \ c \]  
\[ f\ a\ b\ c \]

C, C++, Java, ...
Lisp, Scheme
Smalltalk, Objective C
Haskell, shell scripts
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Meaning:

Execute the named subroutine with its formal arguments bound to the provided actual arguments.
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Parameter passing modes

- By value
- By reference, by sharing
- By value/return
PARAMETER PASSING MODES

Call by value

• A copy of the argument’s value is passed.
• Changes to the formal parameter do not affect the actual parameter.

Call by reference

• The address of the argument is passed.
• Formal parameter is an alias of the actual parameter.
• Changes to the formal parameter affect the actual parameter.
• The actual parameter must be an l-value.
FORTRAN:

- All parameters are passed by reference.
- Temporary variables are used to pass non-l-value expressions.
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Pascal:

• Call by value is the default.
• Keyword var before formal parameter switches to call by reference:
  Example: `procedure sub(a : integer; var b : integer)`
FORTRAN:

• All parameters are passed by reference.
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Pascal:

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  Example: `procedure sub(a : integer; var b : integer)`

C:

• Call by value
• Arrays are passed by value, as pointers
• To simulate call by reference, pass a pointer
Smalltalk, Lisp, Clu, ML:

- Reference model of variables

⇒ Call by sharing: Object can be altered, just as with call by reference but the identity of the object cannot change.
EXAMPLES OF PARAMETER PASSING MODES (2)

Smalltalk, Lisp, Clu, ML:

- Reference model of variables

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Ada:

- **in** parameters: Call by value
- **in out** parameters: Call by reference or call by value/return
- **out** parameters: “Call by result”
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• in parameters: Call by value
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• out parameters: “Call by result”

C++:

• Same as C but with the addition of reference parameters:
  ```cpp
  void swap(int &a, int &b) { int t = a; a = b; b = t; }
  ```
• References can be declared const: efficiency of call by reference and safety of call by value
Java, Python:

- Call by value for primitive types
- Call by sharing for compound types (objects)
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- Call by value for primitive types
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C#:

- Call by value/sharing is the default
- `ref` and `out` keywords to force call by reference
- Distinction between call by value and call by sharing made at data type level:
  - `struct` types are values.
  - `class` types are references.
READ-ONLY PARAMETERS

A common practice in Pascal:

- Large values are passed by reference for efficiency reasons
- High potential for bugs

Modula 3:
- readonly parameters

ANSI C, C++:
- const parameters

When using call by value, declaring a parameter readonly or const is pointless.
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- Safety of call by value

Modula 3: `readonly` parameters

ANSI C, C++: `const` parameters

When using call by value, declaring a parameter `readonly` or `const` is pointless.
Constant definition:

const int buffersize = 512;
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Read-only function parameter:

    void f(const int &i) { ... }
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Immutable reference returned by a function (e.g., container interfaces):

```
const string &f() { ... }
```
SOME USES OF CONST IN C++

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const int buffersize = 512;
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Read-only function parameter:

```cpp
void f(const int &i) { ... }
```

Immutable reference returned by a function (e.g., container interfaces):

```cpp
const string &f() { ... }
```

Object method that cannot change the object (the only type of method that can be invoked on a `const` object):

```cpp
int A::f(int i, string s) const { ... }
```
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Languages that support this:

• Pascal
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• All functional programming languages
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Restricted passing of functions in C/C++ and FORTRAN:

- Functions are not allowed to nest (or not significantly in FORTRAN)
- No need for closures
- Pointers to subroutines suffice
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Default (optional) parameters need not be specified by the caller. If not specified, they take default values.

Ada:

```ada
procedure put(item  : in integer;
               width : int field := 10);
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C++:

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void put(int item, int width = 10) { ... }
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Implementation is trivial. How?
Named (keyword) parameters need not appear in a fixed order.

- Good for documenting the purpose of parameters in a call.
- Necessary to utilize the full power of default parameters.

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C/C++/Python allow variable numbers of arguments:

```c
#include <stdarg.h>

int printf1(char *format, ...) {
    va_list args;
    va_start(args, format);
    char c = va_arg(args, char);
    ...
    va_end(args);
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Java and C# provide similar facilities, in a typesafe but more restrictive manner.
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Standard subroutines allow the same code to be applied to many different values.

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Generic subroutines can be applied to many different types.

There is a trade-off involved in balancing the generality of the framework with type safety.
Examples: Lisp, Scheme, Python, Ruby

```lisp
(defun merge (a b)
  (cond ((null? a) b)
        ((null? b) a)
        ((< (car a) (car b)) (cons (car a) (merge (cdr a) b)))
        (t (cons (car b) (merge a (cdr b))))))
```
**Example: C++ templates**

class A {
  int f();
};

class B {
  // No method f
};

template <class T> class C {
  T data;
  int g() { return data.f(); }
};

C<A> a; // OK
C<B> b; // Error
Examples:

• Java interfaces
• Haskell type classes

```java
public static <T extends Comparable<T>> void sort(T A[]) {
    ...
    if (A[i].compareTo(A[j]) >= 0) {
        ...
    }
    ...
}
```

```java
Integer[] myArray = new Integer[50];
sort(myArray);
```
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### Typical semantics of exception handling

- **Exception handler** lexically bound to a block of code.
- An exception raised in the block replaces the remaining code in the block with the code of the corresponding exception exception handler.
- If there is no matching handler, the subroutine exits and a handler is looked for in the calling subroutine.
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Some (older) languages deviate from this.
USE OF EXCEPTION HANDLERS

• Perform operations necessary to recover from the exception.

• Terminate the program gracefully, with a meaningful error message.

• Clean up resources allocated in the protected block before re-raising the exception.
Representing exceptions:

• Built-in exception type
• Object derived from an exception class
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Raising exceptions:

• Automatically by the run-time system as a result of an abnormal condition (e.g., division by zero)
• `throw/raise` statement to raise exceptions manually
Where can exceptions be handled?

- Most languages allow exceptions to be handled locally and propagate unhandled exceptions up the dynamic chain.
- Clu does not allow exceptions to be handled locally. (How can you simulate local exception handlers?)
- PL/I’s exception handling mechanism is similar to dynamic scoping.
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Some languages require exceptions thrown but not handled inside a subroutine to be declared as part of the subroutine definition.
- “Invent” a value that can be used instead of a real value normally returned by a subroutine.

- Return an explicit “status” value to the caller. The caller needs to check this status.

- Rely on the caller to pass a closure to be called in case of an exception.
• Exception handlers in the current scope are examined in order. The first one that “matches” the exception is invoked.
• If no matching handler is found, the subroutine exits, and the process is repeated in the caller.
• The stack must be unwound (restored to the previous state) and any necessary clean-up needs to be performed (e.g., deallocation of heap objects, closing of file descriptors). Some languages provide support for this using constructs such as Java’s finally clause.
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- Exception handlers with multiple alternatives are implemented using if-then-else or switch statements in the handler.

This implementation is costly because it requires the manipulation of the handler stack for each subroutine call/return.
A faster implementation:

- Store a global table mapping the memory addresses of code blocks to exception handlers (can be generated by compiler).
- When encountering an exception, perform binary search on the table using the program counter to locate the corresponding handler.

Comparison to simple mechanism:

- Handling an exception is more costly (binary search), but exceptions should be rare.
- In the absence of exceptions, the cost of this mechanism is zero!
- Cannot be used if the program consists of separately compiled units and the linker is not aware of this exception handling mechanism.
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Java:

- **throw** throws an exception.
- **try** encloses a protected block.
- **catch** defines an exception handler.
- **finally** defines block of clean-up code to execute no matter what.
- Only **Throwable** objects can be thrown.
- Must declare uncaught checked exceptions.

```java
try {
    ...
    throw ...  
    ...
}
catch (SomeException e1) {
    ...
}
catch (SomeException e2) {
    ...
}
finally {
    ...
}
```
EXCEPTIONS IN JAVA AND C++

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C++:
• `throw`, `try`, and `catch` as in Java
• No `finally` block
• Any object can be thrown.
• Exception declarations on functions not required

```java
try {
    ...
    throw ...
    ...
}
catch (SomeException e1) {
    ...
}
catch (SomeException e2) {
    ...
}
finally {
    ...
}
```
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A continuation is the “future” of the current computation, represented as

- Current stack content and referencing environment
- Current register content
- Current program counter
- ...

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- Current register content
- Current program counter
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Continuations are first-class objects in Scheme: they can be passed as function arguments, returned as function results, and stored in data structures.
(call-with-current-continuation f) calls function f and passes the current continuation to f as an argument.
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**Simplest possible use:** Escape procedure

- If f never uses the continuation it was passed as an argument, then everything works as if f had been invoked as (f).
- If f invokes the continuation, then the program state is restored as if f had never been called.
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- If f invokes the continuation, then the program state is restored as if f had never been called.

**Example:** Look for the first negative number in a list

(call/cc (lambda (exit)
    (for-each (lambda (x)
        (if (negative? x)
            (exit x))
        x))
    '(54 0 37 -3 245 19))

#t)
(define (list-length obj)
    (call/cc (lambda (return)
        (letrec ((r (lambda (obj)
                        (cond ((null? obj) 0)
                              ((pair? obj) (+1 (r (cdr obj))))
                              (else (return #f))))))
            (r obj))))

(list-length '(1 2 3 4)); --> 4
(list-length '(a b . c)); --> #f
In C, `setjmp/longjmp` provide a limited form of continuations:

```c
if (!setjmp(buffer)) {
    /* protected code */
}
else {
    /* handler */
}
```

- The first invocation of `setjmp` returns 0 and stores the current context (registers, stack pointer, ...) in the provided jump buffer.
- If no `longjmp` is performed on the buffer, the then-branch terminates as usual.
- If `longjmp` is invoked, the `setjmp` returns for a second time, with a non-zero return value, and the handler in the else-branch is executed.
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• Coroutines
ROAD MAP

- Functions, procedures, and parameters
- Inline expansion
- Parameter passing modes
- Passing functions as arguments
- Default and named parameters
- Variadic subroutines
- Generic subroutines
- Exception handling
- Continuations
- Coroutines
Coroutines are separate threads of execution that voluntarily transfer control to each other. (Contrast this with threads.)
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Useful to implement generators, e.g., in Python
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Coroutines are “active” at the same time. Thus, they cannot use the same stack. Some notion of stack is required to allow recursion within coroutines and support lexical scoping.

**Solution:** Cactus stack
(define (adder args)
  (let* ((val (car args))
          (other (cdr args))
          (res (call/cc (lambda (c) (other (cons val c))))))
    (if (< (char res) 100)
      (begin (display "Adder: ")
        (display (car res))
        (newline)
        (adder (cons (+ 1 (car res)) (cdr res))))))
>
(adder
  (cons 1
    multiplier))
Adder: 1
Multiplier: 2
Adder: 4
Multiplier: 5

(define (multiplier args)
  (let* ((val (car args))
          (other (cdr args))
          (res (call/cc (lambda (c) (other (cons val c))))))
    (if (< (car res) 100)
      (begin (display "Multiplier: ")
        (display (car res))
        (newline)
        (multiplier (cons (* 2 (car res)) (cdr res)))))))
Adder: 10
Multiplier: 23
Adder: 46
Multiplier: 47
Adder: 94
Multiplier: 95
• **Subroutines** are the main tool for building control abstractions.

• **Parameter passing** modes determine how subroutines interact with the outside world through their parameters.

• **Exception handling** is a mechanism to recover from abnormal situations in a program’s execution.

• **Exceptions should not be used for normal control flow!** (Shame on you, Python!)

• **Coroutines** are elegant tools for implementing cooperative multi-threading.

• **Continuations** subsume subroutines, coroutines, exception handling, ...