SUBROUTINES AND CONTROL ABSTRACTION

PRINCIPLES OF PROGRAMMING LANGUAGES

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ABSTRACTIONS AS PROGRAM BUILDING BLOCKS

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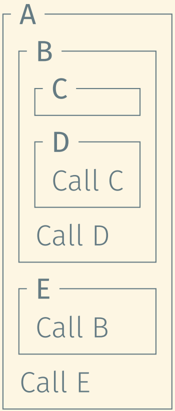
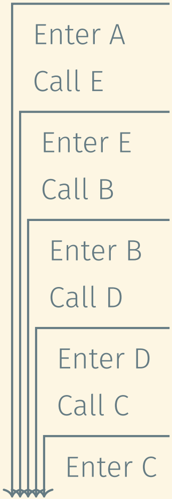
We already discussed activation records or (stack) frames as a means to manage the space for local variables allocated to each subroutine call.

STATIC CHAINS AND DYNAMIC CHAINS

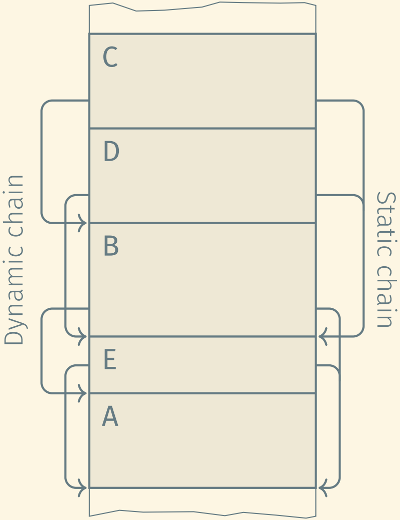
Source code



Program execution



Execution stack



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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)`	C, C++, Java, ...
`(f a b c)`	Lisp, Scheme
`a f: b fcont: c`	Smalltalk, Objective C
`f a b c`	Haskell, shell scripts

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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.

EXAMPLES OF PARAMETER PASSING MODES (1)

FORTRAN:

- All parameters are passed by reference.
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- Call by value is the default.
- Keyword `var` before formal parameter switches to call by reference:
  Example: `procedure sub(a : integer; var b : integer)`

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C:

- Call by value
- Arrays are passed by value, as poisters
- To simulate call by reference, pass a pointer

EXAMPLES OF PARAMETER PASSING MODES (2)

Smalltalk, Lisp, Clu, ML:

- Reference model of variables

$\Rightarrow$ Call by sharing: Object can be altered, just as with call by reference but the identity of the object cannot change.

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- `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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C++:

- Same as C but with the addition of reference parameters:
  `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

EXAMPLES OF PARAMETER PASSING MODES (3)

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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.

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

```
int A::f(int i, string s) const { ... }
```

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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

Default (optional) parameters need not be specified by the caller.
If not specified, they take default values.

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procedure put(item  : in integer;
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- Good for documenting the purpose of parameters in a call.
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VARIADIC SUBROUTINES (VARIABLE NUMBER OF ARGUMENTS)

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

```
#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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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

```
(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))))))
```

GENERIC SUBROUTINES: COMPILE-TIME TYPE CHECKS UPON INSTANTIATION

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

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

Integer[] myArray = new Integer[50];
sort(myArray);
```

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- Exception handler lexically bound to a block of code.
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Some (older) languages deviate from this.

- 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.

EXCEPTION SUPPORT IN PROGRAMMING LANGUAGES (1)

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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

EXCEPTION SUPPORT IN PROGRAMMING LANGUAGES (2)

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.

HANDLING EXCEPTIONS WITHOUT LANGUAGE SUPPORT

- “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.

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- 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.

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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.

EXCEPTIONS IN JAVA AND C++

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.

```
try {
  ...
  throw ...
  ...
}
catch (SomeException e1) {
  ...
}
catch (SomeException e2) {
  ...
}
finally {
  ...
}
```

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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

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  throw ...
  ...
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- Current stack content and referencing environment
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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 IN SCHEME

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- 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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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.

Example: Look for the first negative number in a list

```
(call/cc (lambda (exit)
           (for-each (lambda (x)
                       (if (negative? x)
                         (exit x)))
                     '(54 0 37 -3 245 19))
           #t))
```

CALL/CC FOR EXCEPTION HANDLING

```
(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
```

SETJMP/LONGJMP MECHANISM IN C

In C, `setjmp`/`longjmp` provide a limited form of continuations:

```
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.

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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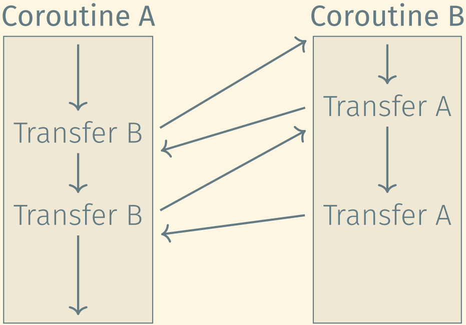
Coroutines are separate threads of execution that voluntarily transfer control to each other. (Contrast this with threads.)



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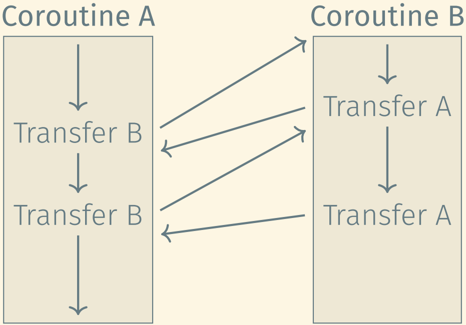

Useful to implement generators, e.g., in Python

MANAGING STACK SPACE FOR COROUTINES

Coroutines are "active" at the same time. Thus, they cannot use the same stack.

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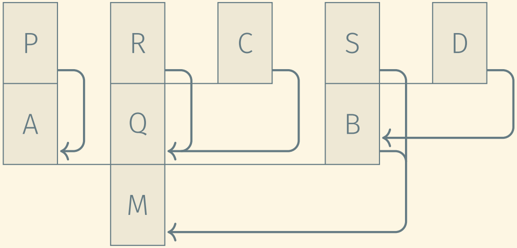
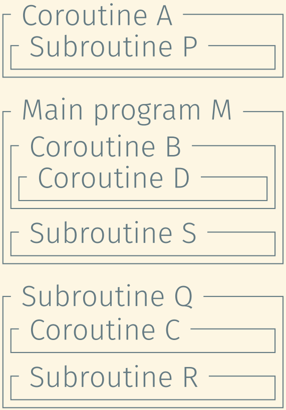
Solution: Cactus stack





```
(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)))))))

(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
    (cons 1
      multiplier))
Adder: 1
Multiplier: 2
Adder: 4
Multiplier: 5
Adder: 10
Multiplier 11
Adder: 22
Multiplier: 23
Adder: 46
Multiplier: 47
Adder: 94
Multiplier: 95
```

SUMMARY

- 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, ...