Closures and Continuations without Functional Programming

November 15, 2001

CS 131: Programming Languages

Callbacks/Upcalls

- When "system" code calls "user" code, this is called a **callback** or **upcall**.
  - Reverses the normal case of user code making calls to the underlying system.
  - Frequently the user function to call is passed to the system via a normal function call.
- Examples:
  - Having a function run every time a GUI button is pressed
  - Having a function run every time a packet arrives on the network
  - Other "event-driven" code

Callbacks in SML

- Suppose we have an interface something like:

```
type button
addCallback : button * (unit -> unit) -> unit
```

- Then, assuming we have buttons `button1` and `button2`:

```
fun f1 () = print "aha"
fun f2 () = print "oho"
val _ = addCallback(button1,f1)
val _ = addCallback(button2,f2)
```

Better Callbacks in SML

- This is ok since `f1` and `f2` are small, but what if each function had to open a new window just to display its string? Lots of code duplication...
- Better structure would be:

```
fun printer s = (fn () => print s)

val b1 = make_button (printer "aha")
val b2 = make_button (printer "oho")
```

Example: X-Windows

- The X Toolkit defines an event-driven model for X-windows
  - Can specify functions to be called when a particular event occurs (e.g, button pressed)
- The X Toolkit includes support for buttons
  - Can tell a button to invoke a function when pressed, by passing a function pointer to the `XtAddCallback` function
  - Function is specified via a function pointer

Callbacks in C

```
void f1(Widget w, XtPointer x, XtPointer y) {
   printf("aha");
}
void f2(Widget w, XtPointer x, XtPointer y) {
   printf("oho");
}
int main() {
   Widget button1, button2;
   /* initialization code for buttons here */
   XtAddCallback(button1, XmNactivateCallback, f1, 0);
   XtAddCallback(button2, XmNactivateCallback, f2, 0);
}
```

Constraints on C Function Pointers

- In C one can pass/return function pointers

```
void qsort
     (void *base,  size_t nel,  size_t  width,
      int (*compar)(const void *, const void *));
```

- But, any function passed to sort must be written completely by the programmer.
  - cannot "create" functions at run-time. (Why?)

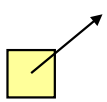
```
fun compare_nth_char n =
  fn (s1:string,s2:string) =>
      String.sub(x,n) > String.sub(y,n)
```

Better Callbacks?

- There is no direct equivalent in C to the `printer` higher-order function.
- If we want two buttons which do similar but slightly different things, must we write two completely separate functions?

Closures vs. Code Pointers

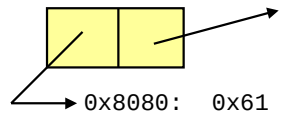
- A function pointer in C is just the address of a piece of code *generated by the compiler*.



```
0x4C00:  add $1, $2, $3
0x4C04:  cmp $2, 3, $5
0x4C08:  bgt $5, 4C16
0x4C12:  ret
0x4C16:  mov $2, $0
0x4C20:  ...
```

Closures vs. Code Pointers

- A function in SML is represented by a *closure*
  - Construct that contains both a pointer to code *and* some data that code can use



```
0x8080:  0x61
0x8081:  0x68
0x8082:  0x61
0x8083:  0x00
```

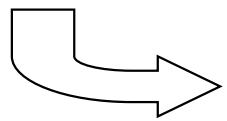
```
0x4C00:  add $1, $2, $3
0x4C04:  cmp $2, 3, $5
0x4C08:  bgt $5, 4C16
0x4C12:  ret
0x4C16:  mov $2, $0
0x4C20:  ...
```

Informal Closures

- We can approximate what's going on in at run-time, using SML source code.
  - A closure is a pair containing a function with no free variables (i.e., code), and some data (the "environment")
  - The function code expects to get the data as an extra argument!
  - Whenever a closure is applied, we need to pass to the code both the "actual" argument and the data part of the closure.

Closure Conversion

```
fun printer s =
 (fn () => print s)

val f1 =
  printer "aha"

f1()
```



```
fun anon_code(s,()) =
     print s
fun printer_code((),s) =
     (s,anon_code)
val printer =
      ((), printer_code)

val f1 =
   (#2 printer)
     (#1 printer, "aha")

(#2 f1)(#1 f1, ())
```

Manual Closures in C

```
void printer(Widget w, XtPointer client_data,
             XtPointer y) {
   printf("%s", client_data);
}

int main() {
   Widget button1, button2;
   /* …initialization code for buttons here… */
   XtAddCallback(button1, XmNactivateCallback,
                 printer, "aha");
   XtAddCallback(button2, XmNactivateCallback,
                 printer, "oho");
}
```

Comparison: POSIX Threads

- The C call to create a POSIX thread is:

```
int pthread_create(pthread_t *new_thread_ID,
                   const pthread_attr_t *attr,
                   void * (*start_func)(void *),
                   void *arg);
```

"The thread is created executing `start_func` with `arg` as its sole argument. If the `start_func` returns, the effect is as if there was an implicit call to `pthread_exit()`"

Continuations in C

- See handout (if interested) on an application of continuations in an operating system.
- Issue:
  - OS is handling many threads/processes at any given time.
  - Each one needs a kernel stack when executing system calls.
  - Many processes may be waiting in the kernel (e.g., for i/o) at the same time, so can't necessarily share a stack.
- Paper's suggestion:
  - Allow a thread that is about to block in the kernel to specify a *continuation* function, called when it's time to restart.
    - Thread responsible for saving all data the continuation will need.
  - Kernel can then safely discard/reuse the thread's kernel stack

Comparison: Java Callbacks

```
class AhaPrinter implements ActionListener {
      public void actionPerformed(ActionEvent e) {
             System.out.print("aha");
      }
}

class OhoPrinter implements ActionListener {
      public void actionPerformed(ActionEvent e) {
             System.out.print("oho");
      }
}

JButton button1 = new JButton("B1");
JButton button2 = new JButton("B2");
button.addActionListener(new AhaPrinter());
button.addActionListener(new OhoPrinter());
```

Improved Java Callbacks

```
class Printer implements ActionListener {
      String s;
      Printer(String s) {this.s = s; }
      public void actionPerformed(ActionEvent e) {
              System.out.print(this.s);
       }
}

JButton button1 = new JButton("B1");
JButton button2 = new JButton("B2");
button.addActionListener(new Printer("aha"));
button.addActionListener(new Printer("oho"));
```

Closures vs. Objects

- What's the difference between an object and a closure?
- What's the difference between a method and a function?

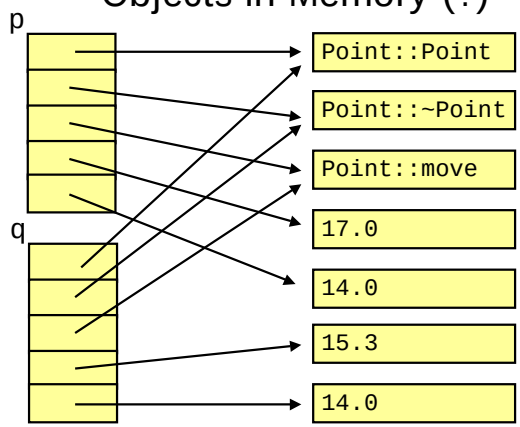
Is SML Object-Oriented?

```
fun newcell() =
  let
     val r = ref 0
  in
     {contents = r,
      get      = (fn() => !r),
      set      = (fn n => (r:=n))}
  end

val mycell = newcell()
val _ = (#contents mycell) := 3
val x = (#set mycell) ((#get mycell)() * 2)
```

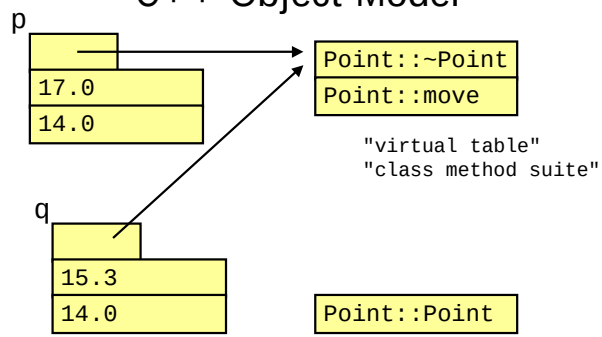
Object Representation

```
class Point {
  public:
     Point (double,double);
     virtual ~Point;
     virtual void move(double,double);
     double x;
     double y;
};

p = new Point(17.0, 14.0);
q = new Point(15.3, 14.0);
```

Objects in Memory (?)



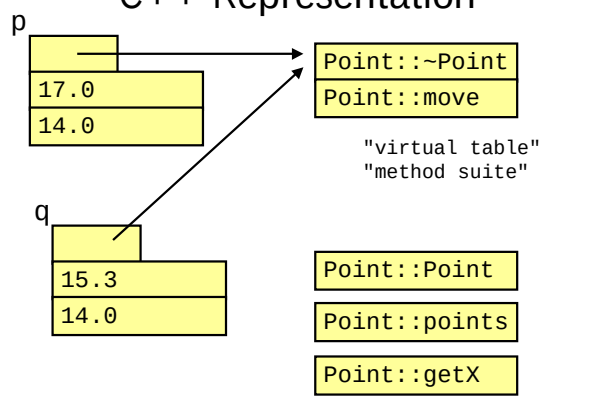
C++ Object Model



Other Class Components

```
class Point2 {
  public:
     Point (double,double);
     virtual ~Point;
     virtual void move(double,double);
     double x,y;
     static int points;
     int getX();
};

p = new Point2(17.0, 14.0);
q = new Point2(15.3, 14.0);
```

C++ Representation



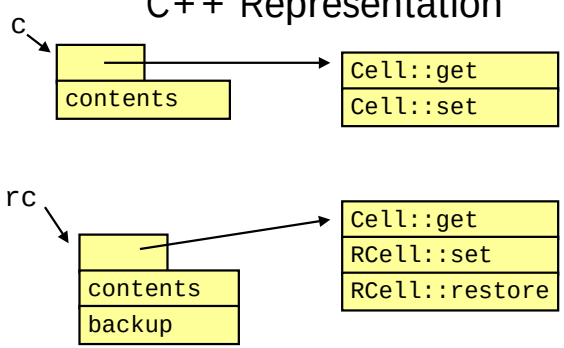
Comments

- Object layout doesn't care about `public / private / protected`
  - These are solely a matter of scoping; the typechecker ensures that abstraction is not violated.
- Interface of a class uniquely determines the class layout.
  - e.g., byte offsets of fields or methods
  - This is why you have to list all the private components of the object.
  - Contributes to "fragile base class" problem.

Objects and Subclasses

```
class Cell {
   int contents;
   virtual int get();
   virtual void set(int);
};
class RCell : public Cell {
   int backup;
   virtual void restore();
   /* overrides set to store contents into backup */
};
Cell *c = new Cell;
RCell *rc = new RCell;
```

C++ Representation



Classes

- Classes in C++ and Java provide
  - Ability to create objects
  - Repository for related code (`static`)
  - Access control (`public`/`private`)
  - Code reuse via inheritance
  - Abstract types
  - Subtyping

Object-*Based* Languages

- Languages with objects don't necessarily require classes
  - Such languages are often called object-*based*
  - Often untyped.
- Where do objects come from, without classes?
  - Where do tuples/records come from in SML?
  - Many object-based languages are organized around "prototypes"
    - Embedding: objects created by cloning a prototype and modifying it (adding or replacing fields/methods)
    - Delegation: objects can contain a pointer to the prototype which handles any method or field referenced they don't know about.

Example: JavaScript

```
function cell_get() {
   return this.contents;
};
function cell_set(n) {
   this.contents = n;
};

var mycell = new Object();
mycell.contents = 0;
mycell.get = cell_get;
mycell.set = cell_set;
```

Example: JavaScript

```
function Cell {
   this.contents = 0;
   this.get = cell_get;
   this.set = cell_set;
};

var mycell = new Cell();
```

Delegation

- Subclassing without classes
- Each object internally references another object, called the prototype
  - If we fail to find a field or method in an object, try looking in the object's parent, the parent's parent, etc.
  - Efficiency: many objects can share the same parent, so they don't have to each have a copy of the parent's fields and methods.
  - Adding methods to the parent causes new code to show up in all the child objects too. (Even built-in objects like strings!)