

CSC 347 - Concepts of Programming Languages

Exercises

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Exercise Topics

- Tail recursion
- Safety, scope and lifetime
- Algebraic datatypes
- Argument passing
- Closures
- Inheritance and delegation
- JavaScript objects and scope



Tail Recursion

```
1 def f (n:Int) = if n<=1 then 1 else n * f (n-1)
2 def g (n:Int) = f (n) * g (n-1)
3 def h (n:Int) = h (g (n), f (n))
4 def i (n:Int) = n * n
```

- Is `f` recursive? tail-recursive?
- Is `g` recursive? tail-recursive?
- Is `h` recursive? tail-recursive?
- Is `i` recursive? tail-recursive?



Tail Recursion

```
1 def f (n:Int) = if n<=1 then 1 else n * f (n-1)
2 def g (n:Int) = f (n) * g (n-1)
3 def h (n:Int) = h (g (n), f (n))
4 def i (n:Int) = n * n
```

- `f` is recursive, but not tail-recursive (multiplication `n*f(n-1)`)
- `g` is recursive, but not tail-recursive (multiplication `f(n) * g(n-1)`)
- `h` is tail-recursive (recursive call to `h` last)
- `i` is not recursive at all



Continuation Passing

```
1 def fact(n: Int) : BigInt =  
2   require (n>=0)  
3   if n <= 1 then 1  
4   else n * fact(n-1)  
5 end fact
```

```
1 def factCPS[X](n: Int, k: _____) : X =  
2   require (n>=0)  
3   if n <= 1 then _____  
4   else factCPS(_____, _____)  
5 end factCPS
```

- Fill in the blanks in the continuation passing style



Continuation Passing

```
1 def fact(n: Int) : BigInt =  
2   require (n>=0)  
3   if n <= 1 then 1  
4   else n * fact(n-1)  
5 end fact
```

```
1 def factCPS[X](n: Int, k: BigInt=>X) : X =  
2   require (n>=0)  
3   if n <= 1 then k(1)  
4   else factCPS(n-1, r => k(n*r))  
5 end factCPS
```



Scope and Lifetime: Dangling Pointers

```
1 int* f(int x) { return &x; }
2 int* g(int x) {
3     int* y = (int*) malloc (sizeof (int));
4     *y=x;
5     return y;
6 }
7 int main(void) {
8     int* p = f(5);
9     printf("%d\n", *p);
10    int* q = g(5);
11 }
```

- Is `p` pointing to the heap or stack?
- Is `p` dangling? Is dereferencing it safe?
- Does `p` need to be freed?
- Is `q` pointing to the heap or stack?
- Is `q` dangling? Is dereferencing it safe?
- Does `q` need to be freed?



Scope and Lifetime: Dangling Pointers

```
1 int* f(int x) { return &x; }
2 int* g(int x) {
3     int* y = (int*) malloc (sizeof (int));
4     *y=x;
5     return y;
6 }
7 int main(void) {
8     int* p = f(5);
9     printf("%d\n", *p);
10    int* q = g(5);
11 }
```

- `p` points to the stack
- `p` is dangling, and dereferencing it is not safe
- `p` points already to freed memory
- `q` points to the heap
- `q` is not dangling, it can be dereferenced safely
- `q` needs to be freed



Unsafe Memory Access

```
1 int* f(int* x) {  
2     *x = *x+1;  
3     return x;  
4 }  
5 int main(void) {  
6     int x = 5;  
7     double y = 5.2;  
8     printf("%d\n", *f(&x));  
9     printf("%f\n", *f(&y));  
10 }
```

- Does the program make an unsafe memory access?
- If so, where?



Unsafe Memory Access

```
1 int* f(int* x) {  
2     *x = *x+1;  
3     return x;  
4 }  
5 int main(void) {  
6     int x = 5;  
7     double y = 5.2;  
8     printf("%d\n", *f(&x));  
9     printf("%f\n", *f(&y));  
10 }
```

- Program makes an unsafe memory access when dereferencing `x`, because it accesses memory that stores a `double` as if it were an `int`



Option Types

```
1 case class Person(name: String, email: Option[String])
2
3 def invite(p: Person, mailSender: String=>Boolean) : Boolean = p.email match
4     case _____ => _____
5     case _____ => _____
6 end invite
7
8 def email(p: Person) : String = _____
```

- Send an email to person `p` using the `mailSender`, depending on whether `p` has an email address
- Return the email address of person `p` as a string, or `"unknown"` if they don't have an address



Option Types

```
1 case class Person(name: String, email: Option[String])
2
3 def invite(p: Person, mailSender: String=>Boolean) : Boolean = p.email match
4   case None      => false
5   case Some(a)   => mailSender(a)
6 end invite
7
8 def invite2(p: Person, mailSender: String=>Boolean) : Boolean =
9   p.email.map(mailSender).getOrElse(false)
10 end invite2
11
12 def email(p: Person) : String = p.email.getOrElse("unknown")
```

- Send an email to person `p` using the `mailSender`, depending on whether `p` has an email address
- Return the email address of person `p` as a string, or `"unknown"` if they don't have an address



Static vs. Dynamic Scope

? What is printed in a statically-scoped vs. dynamically-scoped language?

```
1 var x:Int = 10
2
3 def foo() =
4   x = 20
5 def bar() =
6   var x:Int = 30
7   foo()
8   print(x)
9 def zee() =
10  var x:Int = 40
11  bar()
12  print(x)
13
14 print("bar: "); bar(); println(" " + x)
15 print("zee: "); zee(); println(" " + x)
16 print("foo: "); foo(); println(" " + x)
```



Static vs. Dynamic Scope

? What is printed in a statically-scoped vs. dynamically-scoped language?

```
1 var x:Int = 10
2
3 def foo() =
4   x = 20
5 def bar() =
6   var x:Int = 30
7   foo()
8   print(x)
9 def zee() =
10  var x:Int = 40
11  bar()
12  print(x)
13
14 print("bar: "); bar(); println(" " + x)
15 print("zee: "); zee(); println(" " + x)
16 print("foo: "); foo(); println(" " + x)
```

- Static Scope

```
1 bar: 30 20
2 zee: 30 40 20
3 foo: 20
```

- Dynamic Scope

```
1 bar: 20 10
2 zee: 20 40 10
3 foo: 20
```



Algebraic Datatypes

```
1 enum Expr:  
2   case Literal(x:Int)  
3   case Variable(n:String, v: Option[Expr])  
4   // TODO
```

- ❓ Extend the algebraic datatype for arithmetic expressions with operators `+`, `-`, `*`
- ❓ Are there more than one `-` operator?



Algebraic Datatypes

```
1 enum Expr:
2   case Literal(x:Int)
3   case Variable(n:String, v: Option[Expr])
4   case Plus(l: Expr, r: Expr) // l+r
5   case Minus(l: Expr, r: Expr) // l-r
6   case Neg(e: Expr) // -e
7   case Times(l: Expr, r: Expr) // l*r
```

- ❓ Extend the algebraic datatype for arithmetic expressions with operators `+`, `-`, `*`
- ❓ Are there more than one `-` operator?



Algebraic Datatypes

? Finish the `toInt` method for arithmetic expressions

```
1 enum Expr:
2   case Literal(x:Int)
3   case Variable(n:String, v:Option[Expr])
4   case Plus(l: Expr, r: Expr) // l+r
5   case Minus(l: Expr, r: Expr) // l-r
6   case Neg(e: Expr) // -e
7   case Times(l: Expr, r: Expr) // l*r
```

• Method `toInt`

```
1 def toInt(e: Expr) : Int = e match
2   case Literal(x)           => x
3   case Variable(n, None)    => ???
4   case Variable(_, Some(e)) => toInt(e)
5   // TODO
```



Algebraic Datatypes

? Finish the `toInt` method for arithmetic expressions

```
1 enum Expr:
2   case Literal(x:Int)
3   case Variable(n:String, v:Option[Expr])
4   case Plus(l: Expr, r: Expr) // l+r
5   case Minus(l: Expr, r: Expr) // l-r
6   case Neg(e: Expr) // -e
7   case Times(l: Expr, r: Expr) // l*r
```

- Method `toInt`

```
1 def toInt(e: Expr) : Int = e match
2   case Literal(x)           => x
3   case Variable(n, None)    => ???
4   case Variable(_, Some(e)) => toInt(e)
5   case Plus(l, r)           => toInt(l) + toInt(r)
6   case Minus(l, r)          => toInt(l) - toInt(r)
7   case Neg(e)               => 0 - toInt(e)
8   case Times(l, r)          => toInt(l) * toInt(r)
```



Call-by-value and Call-by-reference

? What is printed in a call-by-value vs. a call-by-reference language?

```
1 def f(a:Int, b:Int) = {  
2   a = b  
3   b = b + 1  
4 }  
5  
6 var x = 5  
7 var y = 10  
8 f(x,y); println(s"x=$x, y=$y")  
9 f(x,x); println(s"x=$x")  
10 f(x,x+2); println(s"x=$x")
```



Call-by-value and Call-by-reference

? What is printed in a call-by-value vs. a call-by-reference language?

```
1 def f(a:Int, b:Int) = {  
2   a = b  
3   b = b + 1  
4 }  
5  
6 var x = 5  
7 var y = 10  
8 f(x,y); println(s"x=$x, y=$y")  
9 f(x,x); println(s"x=$x")  
10 f(x,x+2); println(s"x=$x")
```

- Call-by-value

```
1 x=5, y=10  
2 x=5  
3 x=5
```

- Call-by-reference

```
1 x=10, y=11  
2 x=11  
3 x=13
```



Fold

```
1 val l = List(1,2,3,4,5)
2
3 val sum = l.foldLeft(____) {
4   _____
5 }
6
7 val count = l.foldLeft(____) {
8   _____
9 }
10
11 val countEven = l.foldLeft(____) {
12   _____
13 }
```

- Implement functions using fold



Fold

```
1 val l = List(1,2,3,4,5)
2
3 val sum = l.foldLeft(0) {
4   (s, n) => s+n // _ + _
5 }
6
7 val count = l.foldLeft(0) {
8   (c, _) => c+1
9 }
10
11 val countEven = l.fold(0) {
12   (c, n) => if n%2 == 0 then c+1 else c
13 }
```

- Implement functions using fold



Closures

```
1 def f(): String=>String = {  
2   var s = ""  
3   (t:String) => { s = s + t; s }  
4 }  
5 val a = f()  
6 println(a("x"))  
7 println(a("y"))  
8 println(a("z"))
```

- Does the program compile?
- What is the type of `a` ?
- What is printed?
- What is an OOP approach to the code above?



Closures

```
1 def f(): String=>String = {  
2   var s = ""  
3   (t:String) => { s = s + t; s }  
4 }  
5 val a = f()  
6 println(a("x"))  
7 println(a("y"))  
8 println(a("z"))
```

- Does the program compile?
- What is the type of `a`?
- What is printed?
- What is an OOP approach to the code above?

- `a` is function `String=>String`

- Prints

```
1 x  
2 xy  
3 xyz
```

- Implement with a class

```
1 public class f {  
2   private String s = "";  
3   public String fn(String t) {  
4     s = s+t;  
5     return s;  
6   }  
7 }  
8 f a = new f()  
9 System.out.println(a.fn("x"));
```



Nested Closures

```
1 def f(): ()=>String=>String =  
2   var s = ""  
3   () => {  
4     var i = 0  
5     (t:String) => { s = s + t + i; i = i+1; s }  
6   }  
7 end f  
8 val factory = f()  
9 val a = factory()  
10 val b = factory()  
11 println(a("x"))  
12 println(a("y"))  
13 println(b("z"))
```

- Do `a` and `b` share `s` ? Do they share `i` ?
- What is printed?



Nested Closures

```
1 def f(): ()=>String=>String =  
2   var s = ""  
3   () => {  
4     var i = 0  
5     (t:String) => { s = s + t + i; i = i+1; s }  
6   }  
7 end f  
8 val factory = f()  
9 val a = factory()  
10 val b = factory()  
11 println(a("x"))  
12 println(a("y"))  
13 println(b("z"))
```

- `a` and `b` share `s`, but do not share `i` (each has their own `i`)
- `a` and `b` append to the same `s`, but increment their own `i`, so prints `x0`, `x0y1`, and `x0y1z0`



Inheritance vs. Delegation

```
1 class A:
2     def f() = println("A.f")
3 class B extends A:
4     override def f() =
5         println("B.f")
6         super.f()
7     end f
8     def g() = println("B.g")
9
10 val b:A = new B() // b:B?
11 b.f()
```

```
1 let a = {
2     f: function() {
3         console.log("A.f"); }
4 }
5 let b = {
6     f: function() {
7         console.log("B.f");
8         this.__proto__.f(); },
9     g: function() {
10        console.log("B.g"); }
11 }
12 b.__proto__ = a
13 b.f();
```

- ❓ Does the program compile? If yes, what is printed?
- ❓ Does `b.g()` compile? If yes, what is printed?
- ❓ If no, would it compile with `val b:B = new B()`?



Inheritance vs. Delegation

```
1 class A:
2   def f() = println("A.f")
3 class B extends A:
4   override def f() =
5     println("B.f")
6     super.f()
7   end f
8   def g() = println("B.g")
9
10 val b:A = new B() // b:B?
11 b.f()
```

```
1 let a = {
2   f: function() {
3     console.log("A.f"); }
4 }
5 let b = {
6   f: function() {
7     console.log("B.f");
8     this.__proto__.f(); },
9   g: function() {
10    console.log("B.g"); }
11 }
12 b.__proto__ = a
13 b.f();
```

- The program compiles and prints `B.f A.f`
- `b.g()` does not compile, because variable `b` is of static type `A`
- The program would compile with `val b:B = new B()` and would print `B.g`
- For JavaScript: program executes and also prints `B.f A.f`



Parametric Types

```
1 class A
2 class B extends A
3 var as: List[A] = List(new A(), new B())
```

Which code compiles and why/why not?

- ? `val bs: List[B] = as`
- ? `val bs: List[B] = List(new B(), new B())`
- ? `as = bs` (with `bs: List[B]`)
- ? `val a1: Any = as(0) // a1: A // a1: B`



Parametric Types

```
1 class A
2 class B extends A
3 var as: List[A] = List(new A(), new B())
```

Which code compiles and why/why not?

⚡ `val bs: List[B] = as`

✓ `val bs: List[B] = List(new B(), new B())`

✓ `as = bs` (in Scala, `List` is covariant, `List[B] <: List[A]` from `B <: A`)

✓ `val a1: Any = as(0)`, ✓ `val a1: A = as(0)`, ⚡ `val a1: B = as(0)`



Parametric Wildcard Types

```
1 class A
2 class B extends A
3 val as: Array[A] = Array(new A(), new B())
```

Which code compiles and why/why not?

? `val bs: Array[B] = as ?`

? With subtype wildcard

- `val bs: Array[? <: A] = as ?`
- `bs(0) = new B() ?`
- `val b: B = bs(0) ?`
- `val b: A = bs(0) ?`
- `val b: Any = bs(0) ?`

? With supertype wildcard

- `val bs: Array[? >: B] = as ?`
- `bs(0) = new B() ?`
- `bs(0) = new A() ?`
- `val b: B = bs(0) ?`
- `val b: Any = bs(0) ?`



Parametric Wildcard Types

```
1 class A
2 class B extends A
3 val as: Array[A] = Array(new A(), new B())
```

Which code compiles and why/why not?

⚡ `val bs: Array[B] = as` (arrays are type-invariant)

❓ With subtype wildcard

- ✓ `val bs: Array[? <: A] = as` ?
- ⚡ `bs(0) = new B()` (subtype wildcard makes array read-only)
- ⚡ `val b: B = bs(0)` (parameter type of array is `A`)
- ✓ `val b: A = bs(0)` (parameter type of array is `A`)
- ✓ `val b: Any = bs(0)` (`Any` is a supertype of `A`)

❓ With supertype wildcard

- ✓ `val bs: Array[? >: B] = as`
- ✓ `bs(0) = new B()` (supertype wildcard makes array "write-only")
- ⚡ `bs(0) = new A()` (`B` could have other supertypes)
- ⚡ `val b: B = bs(0)` (some supertype of `B` may have additional subtypes)
- ✓ `val b: Any = bs(0)` (degraded read to `Any` is allowed)



JavaScript Objects

```
1 function f() {  
2   return {  
3     a: 1,  
4     b: "hello"  
5     c: function () { return 2; }  
6   }  
7 }
```

- ❓ What is the result type of function f?
- ❓ What is the result of `f().a` ?
- ❓ What is the result of `f().d` ?
- ❓ What is the result of `f().c()` ?



JavaScript Objects

```
1 function f() {  
2   return {  
3     a: 1,  
4     b: "hello"  
5     c: function () { return 2; }  
6   }  
7 }
```

- Function `f` returns an object
- `f().a` returns `1`
- `f().d` returns `undefined` (because property `d` is not present in the object)
- `f().c()` returns `2`



JavaScript: Function-Scoped Variables

```
1 function f(n) {  
2   var fs = [];  
3   for (var i = 0; i < n; i++) {  
4     var x = i;  
5     fs.push(() => x);  
6   }  
7   return fs;  
8 }
```

- What is the result of `f(3)` and why?
- How can we make the result of `f(3)` be `[() => 0, () => 1, () => 2]` ?



JavaScript: Function-Scoped Variables

```
1 function f(n) {  
2   var fs = [];  
3   for (var i = 0; i < n; i++) {  
4     var x = i;  
5     fs.push(() => x);  
6   }  
7   return fs;  
8 }
```

- `f(3)` returns `[()=>2, ()=>2, ()=>2]` because `var` makes `x` function-scoped and `var x` is therefore hoisted outside the loop to the start of function `f`
- `f(3)` becomes `[()=>0, ()=>1, ()=>2]` when we use `const` or `let` (block-scope)