A workshop on monads with C++14

Meetup C/C++ de Madrid
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Madrid, January 2015

Workshop styles

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Potential outcome

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Prerequisites

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- You are expected to be reasonably fluent with some post-2003 C++ stuff
  - **`auto`**
  - **`std::function`**, lambda functions, generic lambda functions
  - Function return type deduction, trailing return type declaration
  - Template template parameters (this is C++03, anyway)
  - **`decltype`**, **`std::declval`**
- You are encouraged to pre-read about functional programming and monads
  - For instance, go to **github.com/joaquintides/usingstdcpp2014**
- You are required to bring a computer with
  - Internet access (hopefully provided by host)
  - A C++14 compiler such as GCC 4.9 (**`-std=c++1y`**) with a recent Boost distro
  - Alternatively, you can use an online environment such as Coliru (**coliru.stacked-crooked.com**)

Maybe Monad

optional<T>

opt1.cpp

```
template<typename T>
struct optional
{
  optional(const T& x);
  optional(none_t);

  const T& get()const;
  T&       get();

  operator bool()const; // sort of
};

optional<double> inv(double x){
  if(x==0.0)return none;
  else      return 1.0/x;
}

optional<double> sqr(double x){
  if(x<0.0)return none;
  else     return std::sqrt(x);
}

optional<double> arcsin(double x){
  if(x<-1.0||x>1.0)return none;
  else             return std::asin(x);
}
```

Exercise

opt2.cpp

- Implement the following composition of functions

```
optional<double> ias(double x)
{
  // return inv(arcsin(sqrt(x))) where it makes sense
}
```

Exercise

opt3.cpp

- Implement this helper function

```
template<typename F>
optional<double> call(const optional<double>& x, F f)
{
  // call f if x is valid, none otherwise
}
```

- Implement **`ias`** using **`call`**

Exercise

opt4.cpp

- Now **inv** is modified so that it truncates its result to **int**:

```
optional<int> inv(double x)
{
  if(x==0.0)return none;
  else      return int(1.0/x);
}
```

- Modify **call** and **ias** to cope with type mismatches

A minimal monadic framework

opt5.cpp

```
template<template<typename> class M,typename T>
M<T> mreturn(const T& x)
{
  return x;
}

// must be overloaded
template<template<typename> class M,typename T,typename F>
auto operator>>=(const M<T>& m, F f)->decltype(f(std::declval<const T>()));
```

- Signatures

return : $T \rightarrow M\text{<}T\text{>}$

$>>=$: $(M\text{<}T\text{>}, T \rightarrow M\text{<}T'\text{>}) \rightarrow M\text{<}T'\text{>}$

List Monad

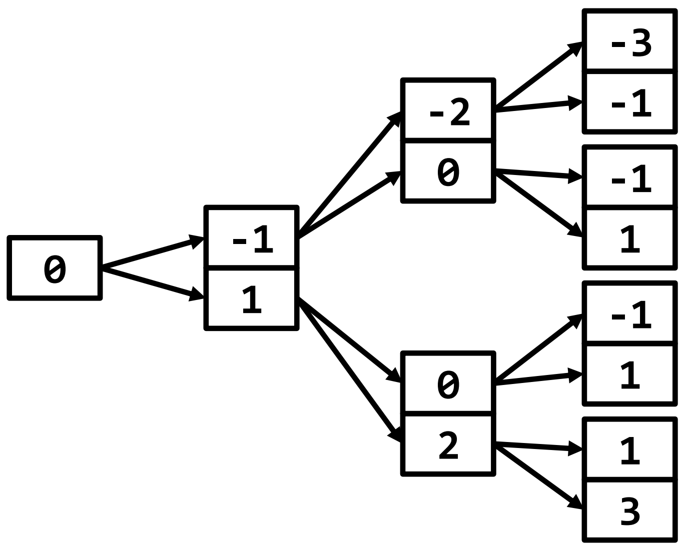
`list` (function composition) as a monad

list1.cpp

```
template<typename T> struct list:std::list<T>
{
  using base=std::list<T>;
  using base::base;
  list(const T& x):base(1,x){} // compatibility with mreturn
};

list<int> decinc(int x){return {x-1,x+1};}
```

- How do we compose **`decinc`** with itself?



- Hint: returning lists is like having multiple potential results
- Hint: look at the signature of **`>>=`**

Exercise (bonus points!)

list2.cpp

- Define `>>=` for `list`

```
template<typename T,typename F>
auto operator>>=(const list<T>& l, F f)
{
 // ...
}
```

- Calculate

```
((decinc(0)>>=decinc)>>=decinc)
```

- Calculate

```
list<int>{0,1,4,5}>>=decinc
```

Exercise

list3.cpp

- Define **`transform`** in terms of **`>>=`** (generically!)

```
template<template<typename> class M,typename T,typename F>
auto transform(const M<T>& m,F f)
{
  // ...
}
```

- Hint: **F**: **T** $\rightarrow$ **R**, but **`>>=`** expects **F'**: **T** $\rightarrow$ **`M<R>`**
- Calculate

```
transform(list<int>{0,1,2},[](int x){return x+1;}
```

- What will these be?

```
transform(optional<int>{1},[](int x){return x+1;})
transform(optional<int>{none},[](int x){return x+1;})
```

Exercise (extra bonus points!)

list4.cpp

- List comprehension:

```
{x+1 | x <- [0 1 2]}
```

implemented as

```
list<int>{0,1,2}>>=[](int x){return mreturn<list>(x+1);}
```

- Implement

```
{x+y | x <- [0 1 2], y <- [1 2 3]} // [1 2 3 2 3 4 3 4 5]
```

do notation

```
{x+y | x <- [0 1 2], y <- [1 2 3]}
```

- Equivalent in **do** notation (Haskell, beware **`return`** is a monadic function, not the C++ keyword)

```
do x <- [0 1 2]
   y <- [1 2 3]
   return (x + y)
```

equivalent to (Haskell)

```
[0 1 2] >>= \ x ->
   [1 2 3] >>= \ y ->
     return (x + y)
```

translated to (C++)

```
list<int>{0,1,2}>>=[&](int x){
  return list<int>{1,2,3}>>=[&](int y){
    return mreturn<list>(x+y);
  };
}
```

Emulating **do** notation in C++

list5.cpp

- Do you hate macros?

```
#define DO(var,monad,body)       \
((monad)>>=[=](const auto& var){ \
  return body;                   \
})
```

- Just for recreational purposes

```
auto res=
  DO(x,list<int>({0,1,2}),
  DO(y,list<int>({1,2,3}),
     mreturn<list>(x+y)
  ));
```

Homework (extra bonus points!)

list6.cpp

- Implement

```
{x+y | x <- [0 1 2], y <- [1 2 3], even (x+y)}
{x+y | x <- [0 1 2], even x, y <- [1 2 3]}
{x+y | x <- [0 1 2], y <- [1 2 3], even y}
{(x,y) | x <- [0 1 2], y <- [1 2 3]}
{(x,y) | x <- [0 1 2], y <- [1 2 3], (even x) || (even y)}
```

- Hint: use a **`filter`** helper defined like this

```cpp
template<typename Pred>
auto filter(Pred pred)
{
  // return function object that accepts some x and returns
  // mreturn<list>(x) if pred(x) or an empty list otherwise
}
```

Recap so far

Recap so far

- Monads are type constructors (aka class templates) along with operations **return** and **>>=** for *T* → *M*<*T’*> function composition
- Monads are a **design pattern** for composition of functions returning **extended types**
  - An extended type *M*<*T*> is a “container” with 0 or more *T* values
- Monad contents can **only** be read via **>>=**
  - This allows for controlled access and execution semantics
- What other value-holding types can be seen as monads?
- **do** notation emulates imperative style in a functional setting
- What about the **monadic laws**, Cap’n?
  - Trust your heart (just kidding)

Continuation Monad

Continuation Passing Style (CPS)

cont1.cpp

- In CPS functions are equipped with a continuation or callback object to feed the result to

```
template<typename C>
auto add(int x,int y,C c){return c(x+y);}

template<typename C>
auto square(int x,C c){return c(x*x);}

template<typename C>
auto pyth(int x,int y,C c) // x*x + y*y
{
  return square(x,[=](int xx){
    return square(y,[=](int yy){
      return add(xx,yy,c);
    });
  });
}

int main()
{
  pyth(3,4,[](int r){std::cout<<r<<"\n";});
}
```

(example adapted from **en.wikibooks.org/wiki/Haskell/Continuation_passing_style**)

A twist of syntax

- Say we return some suitable continuation object rather than accept one

```
template<typename T>
class cont
{
public:
  cont(const T& x):run_([=](){return x;}){}

  T run()const{return run_();}

private:
  std::function<T()> run_;
};

auto add(int x,int y){return cont<int>(x+y);}

auto square(int x){return cont<int>(x*x);}

auto pyth(int x,int y){ /* ?? */ }
```

- How do we compose continuation objects?
- Let's look at the **compositional** interface of **cont**

Exercise

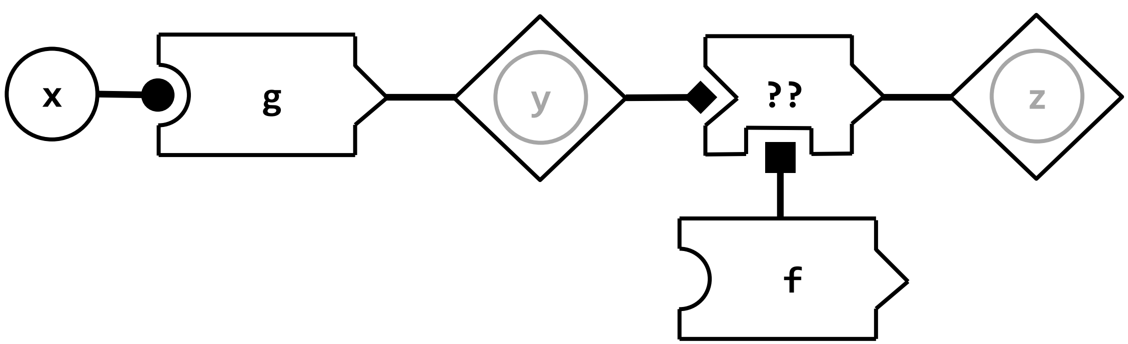
- Figure out the implementation of **`cont`** composition ctor

```
template<typename T>
class cont
{
public:
  // ...

  template<typename F>
  cont(const cont& c,F f):run_(/* figure this out */){}

  //...

private:
  std::function<T()> run_;
};
```



cont is a monad!

cont2.cpp

- I guess you saw it coming ☺

```
template<typename T,typename F>
auto operator>>=(const cont<T>& c, F f)
{
  return cont<T>{c,f};
}

auto pyth(int x,int y)
{
  return
  DO(xx,square(x),
  DO(yy,square(y),
     add(xx,yy)
  ));
}
```

- Not a real monad: we've made a simplifying assumption (which?)
- Not the Haskell standard Continuation Monad, either
  - We map T to $() \to T$, Continuation Monad maps T to $(T \to R) \to R$
  - More like a “Future” Monad, actually

Exercise

cont3.cpp cont3+.cpp cont3++.cpp

- Recursively construct a continuation object that computes factorial

```
cont<int> fac(int n);

int main()
{
  auto f=fac(5);
  std::cout<<"running f\n";
  auto r=f.run();
  std::cout<<"fac(5)="<<r<<"\n";
}
```

- Bonus points: do it lazily (i.e. continuation chain is constructed at **`f.run()`** time)
- Extra bonus points: do it tail-recursively

Homework

cont4.cpp cont5.cpp

- Make our monad general

```
template<typename T,typename F>
auto operator>>=(const cont<T>& c, F f);
// f: T -> cont<T'> with T' not necessarily the same as T
```

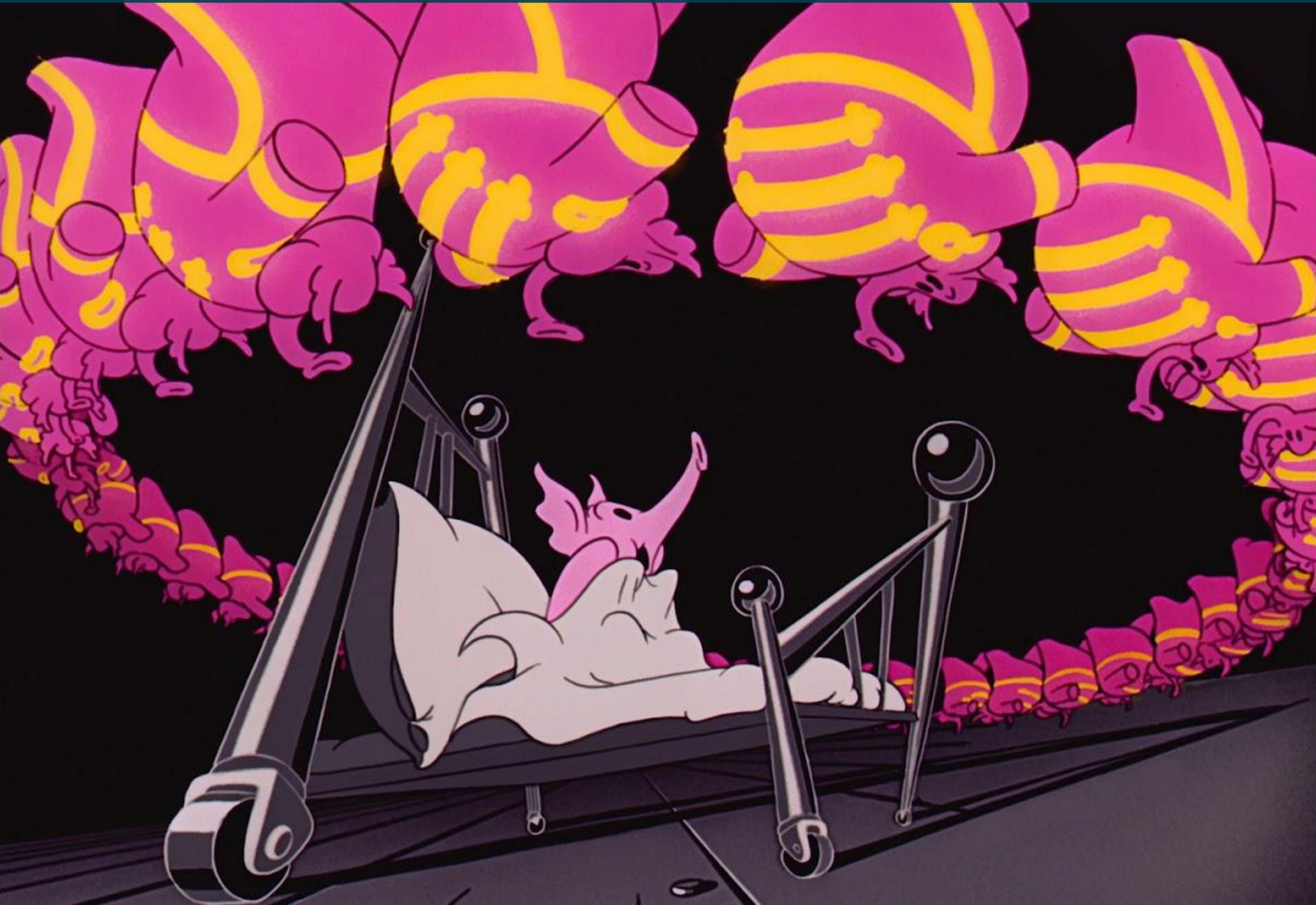
- Extra bonus points: Implement a (restricted) monad with stepwise computation

```
template<typename T>
class cont
{
public:
  // ...
  std::pair<T,boost::optional<cont>> step()const;
  // ...
};
```

Discussion

- Why is this monad interesting?
- The mother of all monads
- The Continuation Monad captures execution flow
- Imperative style in non-imperative settings
- Name application scenarios
- Which C++ entities resemble the Continuation Monad?

I see monads everywhere!



I see monads everywhere!

- Monads are a **design pattern** for composition of functions returning **extended types**
- In Haskell, monads + **do** emulate side-effects and imperative style
- In C++, monads are increasingly showing up
  - **`std::expected`** proposal
  - **`then`**-like extensions to **`std::future`**
- Have a look at “Resumable Functions (rev 3)” proposal (N4286)
  - **`await`** could potentially be extended to act as a monadic **`>>=`**
- My dream: C++ monadic GUI based on functional reactive programming

If you want to learn more about monads…

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- "Monad tutorials online" compiles all relevant Internet stuff by time of publication! **haskell.org/haskellwiki/Monad_tutorials_timeline**
- "All about monads" **haskell.org/haskellwiki/All_About_Monads** is very comprehensive but assumes you know Haskell
  - Take a look at the monad catalog it provides
- Gabriel Gonzalez's "Haskell for all" **haskellforall.com**
  - Very readable even if you don't know the language, monads and more
- "Bartosz Milewski's Programming Cafe" **bartoszmilewski.com** has some monadic stuff as applied to C++
  - "Rediscovering Monads in C++" has many interesting ideas **slideshare.net/sermp/rediscovering-monads**
  - Bartosz's writing a book on Category Theory for programmers, due 2015
- My blog **bannalia.blogspot.com** has some (maybe not too friendly) articles on monads for C++ and C++ template metaprogramming

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Thank you

github.com/joaquintides/cpp14monadworkshop

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