PA5 Notes; Templates

ITP 435
Week 8, Lecture 1

PA5

- You will implement a “virtual machine”/“emulator” for the classic ITP-11 computer system with the Turtle Processing Unit™

- Features of this advanced system include:
  - Fifteen 32-bit integer registers
  - 1 KB of stack space
  - 3-bit color graphics (eight total colors!!!)

PA5

- Why?
  - Be the machine
  - We can use template metaprograms, exceptions, some other C++ features
  - It’s fun!

Parsing Input file

- The input files contain one or more commands, like this:

```
movi tx,110
movi ty,105
movi tc,1
pendown
mov r7,r0
movi r6,5
movi r1,100
movi r2,144
fwd r1
add tr,tr,r2
inc tc
inc r7
cmplt r7,r6
movi r5,6
jt r5
exit
```

Parsing Input file

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movi tx,110
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cmplt r7,r6
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exit
```

- Some take no parameters
- Some take a single parameter
- Some take a comma-separated list of parameters
- Some parameters are integers, some are strings (register names)

Doing this without template metaprograms

- We'd first declare a base class for all ops:

```
struct Op
{
   virtual const char* GetName() const = 0;
   virtual void Parse(const std::string& params) = 0;
   virtual void Execute(class Machine& machine) = 0;
};
```

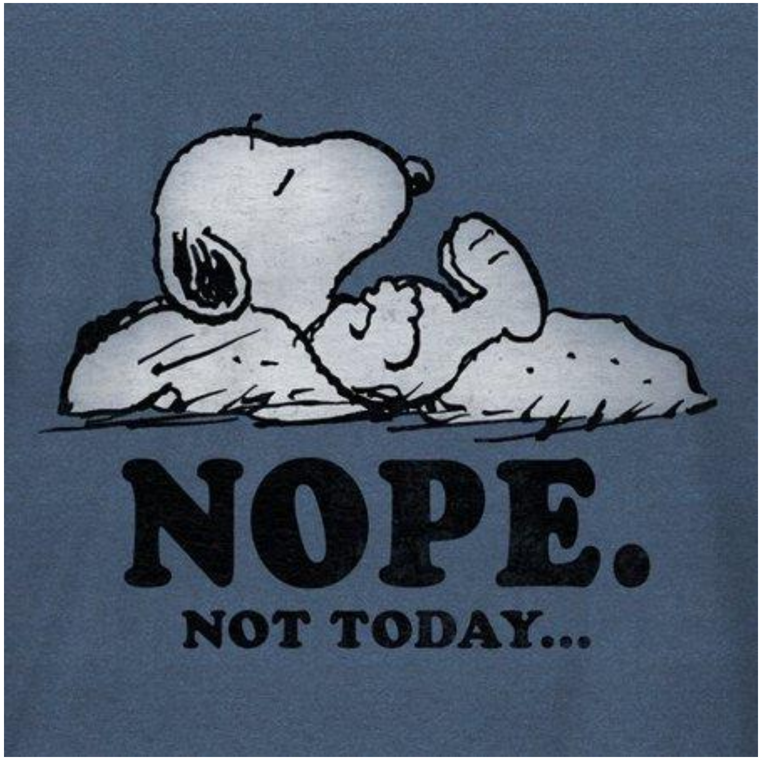
Doing this without template metaprograms

- Then maybe make a subclass for each op, like:

```
// movi reg1,int
// reg1 = int
struct MovI : Op {
   const char* GetName() const override { return "movi"; }
   void Parse(const std::string& params) override {
      // Split comma-separated list
      std::vector<std::string> paramV = Split(params);
      opReg1 = paramV[0]; // This is a string
      opInt = std::stoi(paramV[1]); // Gotta convert this to int!
   }
   void Execute(class Machine& machine) override
   { /* Do whatever */ }
   // Member data for this op!
   std::string opReg1;
   int opInt;
};
```

Doing this without template metaprograms

- Now repeat writing that parse function, and specifying member data for each of the 20+ different ops!
- I say…



We have a pattern

- Every op takes in a comma-separated list of 0 or more params
- We need member data to store each param with the correct type
- We want to convert each param to the desired type (if needed)

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- Every op takes in a comma-separated list of 0 or more params
- We need member data to store each param with the correct type
- We want to convert each param to the desired type (if needed)
- We want to define this pattern, and ***make the compiler generate*** the correct member data/parsing code for each op!

Into the Template Rabbit Hole

Template Metaprogramming (TMP)

- Discovered by accident while templates were being standardized
- Is Turing-complete
- We can define and use templates such that at compile time, they will instantiate to different instances of the template that give us what we want…

Basic Template Syntax (classes)

```
template <typename T>
class List
{
      // ...
};
```

Basic Template Syntax (functions)

```
template <typename T>
T max(T a, T b)
{
      return ((a > b) ? a : b);
}
```

Compiler Instantiation

- If you use this template in code as such:

```
max(1, 2); // Type not specified, compiler attempts substitution
max<char>('a', 'b'); // Type specified (optional)
```

- Compiler will instantiate two versions of our function:

```
int max(int a, int b)
{
     return ((a > b) ? a : b);
}

char max(char a, char b)
{
     return ((a > b) ? a : b);
}
```

Template Specialization

- Suppose you want to do something specific in max when the type is std::string (kinda weird in this example)

- You can then specify a specialization:

```
template <>
std::string max<std::string>(std::string a,
  std::string b)
{
     // Code specific for this case
}
```

std::tuple

- Tuples are like std::pair, except they can have zero to infinite members

- You can use the terminology like this:
  - 0-tuple = Empty
  - 1-tuple = Has one element
  - 2-tuple = Has two elements (it’s a pair)
  - 3-tuple = Has three elements
  - …

An empty tuple

- Although it seems weird, you can declare 0-tuple if your heart desires

```
std::tuple<> empty;
```

A 3-tuple example

- This example is more useful

```
// This has three members (an int, a char, and a float)
std::tuple<int, char, float> tuple3;

// Once constructed, use std::get<idx>
// to access a member of the tuple
// (Both for setting and getting the value)
std::get<0>(tuple3) = 50; // Set int member
char c = std::get<1>(tuple3); // Get char member

// The index passed to get MUST BE CONSTANT AT COMPILE TIME!!
```

std::make_tuple

- If I want to save typing and know what values I want to construct for my tuple, I can use make_tuple:

```
auto myTuple = std::make_tuple(50, "Hello", 10.0);
// myTuple has
// 0 - An int (50)
// 1 - A const char* pointing to "Hello"
// 2 - A double (10.0)
```

std::tuple_cat

- Given 0 or more tuples, constructs a tuple concatenating the tuples together

```
auto myTuple = std::make_tuple(1337);
auto otherTuple = std::make_tuple(std::string("Yo!"));

auto cat = std::tuple_cat(myTuple, otherTuple);
// cat has
// 0 - An int (1337)
// 1 - A std::string containing "Yo!"
```

The first insight

- We want to convert the input comma-separated string into a tuple of the correct types
- This is easier said than done
- We need to know the tuple types at compile time
- So, we have to be generate types through template magics based on the expected parameters

The ground floor

- Given an input string of a single element, we want to be able to convert it to a 1-tuple of the expected type
- Here is the generic template version…note I make it uncompilable by not actually returning anything

```
// Generic version of ParseElem
// If this generic version is instantiated, it won't compile
template <typename T>
std::tuple<T> ParseElem(const std::string& elem)
{ }
```

ParseElem specializations

- Next, I make specializations that convert string to tuple<int> or to tuple<string>

```
// Specialization of ParseElem<int>
// Converts elem to a tuple{int}
template <>
inline std::tuple<int> ParseElem<int>(const std::string& elem) {
   return std::make_tuple(std::stoi(elem));
}

// Specialization of ParseElem<std::string>
// Just makes a tuple{str} from elem
template <>
inline std::tuple<std::string>
   ParseElem<std::string>(const std::string& elem) {
   return std::make_tuple(elem);
}
```

How would I use ParseElem?

```
// This will give us a tuple<int>
auto a = ParseElem<int>("11");

// This will give us a tuple<string>
auto b = ParseElem<std::string>("r1");

// This won't compile
auto c = ParseElem<double>("50.0");
```

ParseStr – The secret sauce begins

- Now we declare a function called ParseStr that:
  - Has 0 or more template parameter types
  - Returns a tuple corresponding to the 0 or more template types
  - Takes in a vector of strings (the different parameter strings)

```
template <typename... Args>
std::tuple<Args...> ParseStr(std::vector<std::string>& paramV);
```

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- Now we declare a function called ParseStr that:
  - Has 0 or more template parameter types
  - Returns a tuple corresponding to the 0 or more template types
  - Takes in a vector of strings (the different parameter strings)

```
template <typename... Args>
std::tuple<Args...> ParseStr(std::vector<std::string>& paramV);
```

- The … syntax is a ***variadic template***, a template that takes in zero or more types
- Notice how we can directly pass that list of types into the template parameter of std::tuple

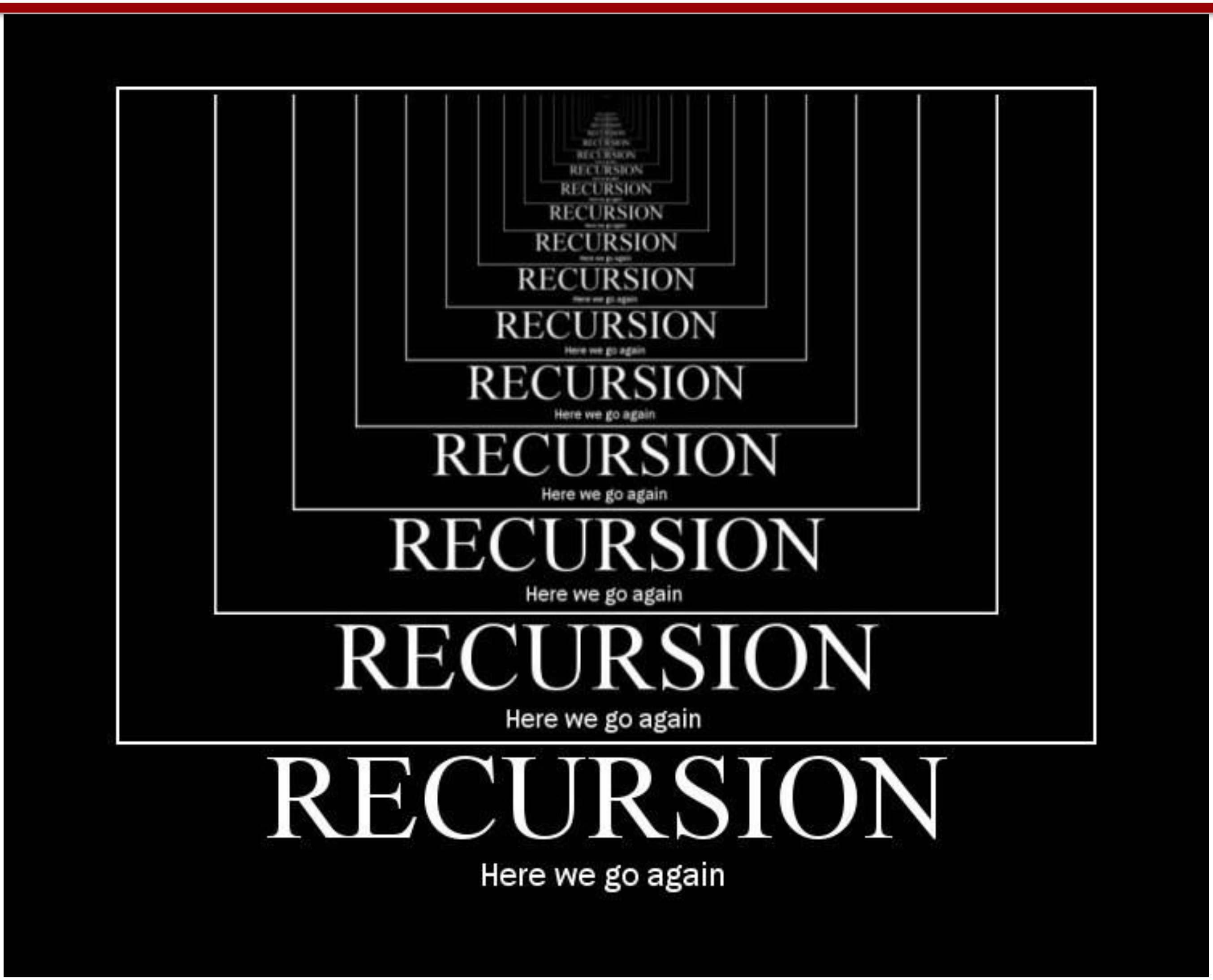
ParseStr – Specialization for zero types

- We make a specialization for where there are no types passed to the template:

```
template <>
inline std::tuple<> ParseStr<>(std::vector<std::string>& paramV)
{
    return std::make_tuple();
}
```

- This is going to serve as a "base case"

Uh oh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Recursive Templates

```
// Calculate a Fibonacci number at COMPILE TIME
template <unsigned int i>
struct Fibonacci {
   static const int value = Fibonacci<i - 2>::value + Fibonacci<i - 1>::value;
};
// The "base cases" are i == 0 or i == 1
// So use specialization...
template <>
struct Fibonacci<0> {
   static const int value = 0;
};
template <>
struct Fibonacci<1> {
   static const int value = 1;
};
// This would be 610 (at COMPILE TIME)
Fibonacci<15>::value
```

ParseStrHelper – Declaration

- Declare ParseStrHelper, which has these template params:
  - A single type T
  - Zero or more additional types Args

```
template <typename T, typename... Args>
std::tuple<T, Args...> ParseStrHelper(std::vector<std::string>& paramV)
```

- Notice how again, we forward the types in that order to the tuple

ParseStrHelper – Declaration

```
template <typename T, typename... Args>
std::tuple<T, Args...> ParseStrHelper(std::vector<std::string>& paramV)
```

- Using this pattern allows us to separate the first type in the template parameters from the remainder
- We want to convert the first type with ParseElem and forward the remaining to a recursive call of ParseStr!

ParseStrHelper – Implementation

```
template <typename T, typename... Args>
std::tuple<T, Args...> ParseStrHelper(std::vector<std::string>& paramV)
{
   // Get the last string from the vector
   // This assumes paramV is in reverse
   std::string elem = paramV.back();
   paramV.pop_back();

   // ParseElem<T>(elem) takes elem and converts it into a tuple{T},
   //
   // Then, take the remaining elements in paramV, and pass
   // it to ParseStr for the remaining variadic types (Args...)
   // (This is the recursive step)
   ///
   // Concatenate these tuples with tuple_cat
   return std::tuple_cat(ParseElem<T>(elem),
      ParseStr<Args...>(paramV));
}
```

ParseStr – Generic implementation

- All ParseStr does is forwards the arguments to ParseStrHelper

- You need this extra indirection so ParseStrHelper can separate the first type from the rest

```
template <typename... Args>
std::tuple<Args...> ParseStr(std::vector<std::string>& paramV)
{
    return ParseStrHelper<Args...>(paramV);
}
```

It's complicated.

- Yes, it is
- Luckily, I just showed you all the code…you just have to type it into your program

ParseStr in action

- Suppose I have this code:

```
std::vector<std::string> paramV = {"5", "r1"};
auto t = ParseStr<std::string, int>(paramV);
```

ParseStr in action

```
std::vector<std::string> paramV = {"5", "r1"};
auto t = ParseStr<std::string, int>(paramV);
```

At compile, time, the compiler has to “instantiate” all the templates we just declared, starting from the top:

- ParseStr<Args={std::string, int}>
  - ParseStrHelper<T=std::string, Args={int}>
    - ParseElem<T=std::string>
    - ParseStr<Args={int}>
      - ParseStrHelper<T=int, Args={}>
        - ParseElem<T=int>
        - ParseStr<Args={}>

ParseStr in action

```
std::vector<std::string> paramV = {"5", "r1"};
auto t = ParseStr<std::string, int>(paramV);
```

This means the type of t is:

std::tuple<std::string, int>

ParseStr in action

```
std::vector<std::string> paramV = {"5", "r1"};
auto t = ParseStr<std::string, int>(paramV);
```

After executing this code:

- std::get<0> gives me a string with “r1”
- std::get<1> gives me an int with 5

It’s in reverse, but that’s intentional

Back to Ops, Back to Reality

- So how do we leverage this for the ops?

```
template <typename... Args>
struct OpBase : Op
{
    void Parse(const std::string& params) override
    {
        // Split
        std::vector<std::string> paramV = Split(params);
        // Reverse vector for simplicitly of template metaprogram
        std::reverse(paramV.begin(), paramV.end());
        // Generate the tuple
        mParameters = ParseStr<Args...>(paramV);
    }

    // Tuple to hold op arguments
    std::tuple<Args...> mParameters;
};
```

MovI

- Now declare the op as a subclass of OpBase with the correct template parameters:

```
// movi reg1,int
// reg1 = int
struct MovI : OpBase<std::string, int>
{
   const char* GetName() const override { return "movi"; }
   void Execute(class Machine& machine) override
   { /* Still have to implement this/ }
};
```

MovI

```
struct MovI : OpBase<std::string, int>
```

This means that…

- MovI will have an mParameters tuple with:
  - 0 – String name of register
  - 1 – Integer value to store in register

- The correct Parse function is automatically generated for you by the template metaprogram!

In-class activity

One More Thing…

Constructing the Correct Op Subclass

```
// Open the file
while (/* Not eof */) {
   // Get the string for op name and params
   std::string opName = /*blah*/;
   std::string params = /*blahblah*/;
   std::shared_ptr<Op> ptr;
   if (opName == "movi") {
      ptr = std::make_shared<MovI>();
   } else if (opName == "exit") {
      ptr = std::make_shared<Exit>();
   } else if (opName == "add") {
      ptr = std::make_shared<Add>();
   }
   // Yikes.........
   // .........
   ptr->Parse(params);
}
```

We have a pattern

- Given a string corresponding to the op, we want to construct a shared pointer to the correct type

- We want a map where:
  - Key is string name of op
  - Value is a “factory method”/“creator function” that knows how to construct said type

The CreateOp template function

- All it does is calls make_shared on the desired op subclass T

```
template <typename T>
std::shared_ptr<Op> CreateOp()
{
    return std::make_shared<T>();
}
```

- (This has to be a standalone or static function)

Now let's declare our map

```
std::map<std::string,
    std::function<std::shared_ptr<Op>()>>
    opMap;
```

- The key type is std::string (name of op)
- The value type is a function that takes in no parameters and returns a std::shared_ptr<Op>

Add Elements to the Map

```
opMap.emplace("movi", &CreateOp<MovI>);
```

- This says that for “movi” call CreateOp<MovI>

Now with the map

- Look how simple our code is

```
while (/* Not eof */0) {
   // Get the string for op name and params
   std::string opName = /*blah*/;
   std::string params = /*blahblah*/;

   // Look up the opName in our map, and call the
   // correct CreateOp function! (note the extra
   // parenthesis at the end, that's the function call)
   std::shared_ptr<Op> ptr = opMap.at(opName)();
   ptr->Parse(params);
}
```

And Just For Fun…

For more fun…

- We can meta-metaprogram via the power of X-macros, you could also generate those map entries
- You could even use X-macros to auto-generate all the OpBase subclass declarations!

If we want to X-Macro…

- Make a Ops.def file, like:

```
// Define all the ops our VM supports, along with parameters
// Syntax: OP(textName, className, args...)
OP(exit,Exit)
OP(movi,MovI,std::string,int)
OP(add,Add,std::string,std::string,std::string)
OP(mov,Mov,std::string,std::string)
//...
```

To declare the Op subclasses

```
// Define version of OP macro that creates declaration
// __VA_ARGS__ is an expansion of variadic arguments
#define OP(textName,className,...) \
struct className : OpBase<__VA_ARGS__> \
{ \
   const char* GetName() const override { return #textName; } \
   void Execute(class Machine& machine) override; \
};

// This will take definitions and apply OP macro to each
#include "Ops.def"

// Undefine the OP macro
#undef OP
```

To declare the opMap

```
// This macro converts a single OP definition to the appropriate
// {key,value} pair entry in the map
#define OP(textName,className,...) { #textName, &CreateOp<className> },

std::map<std::string, std::function<std::shared_ptr<Op>()>> opMap =
{
#include "Ops.def"
};

#undef OP
```

Should we do this?

- We ***can*** do this, but ***should*** we?

- It may make our code more difficult to follow, debug, and our fellow developers may hate us

- But it still is a cool trick to have up your sleeve for special occasions!