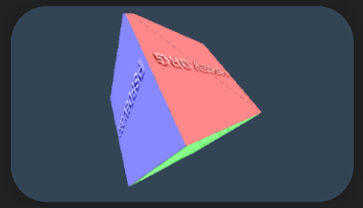
GENERATIVE PROGRAMMING & DECLARATIVE INTERFACES

Emulating the Nintendo 3DS



Tony Wasserka
@fail_cluez

C++ now

Aspen
8 May 2018

WHO AM I?

- C++ enthusiast: Low-level & type-safety
- Game console emulation: GC/Wii/3DS/PSP

PPSSPP

Dolphin

Citra

- Twitter: @fail_cluez
- GitHub: neobrain

- Available for contracting:
  OS kernels, device drivers, embedded systems

WHAT IS THIS ABOUT?

- Serialization & emulation
- Case study: InterProcess Communication (IPC)
- How does generative programming help?
- What can be automated and how?
- How can we maximise reuse?

EMULATION & SERIALIZATION

High-Level Software:

Module A

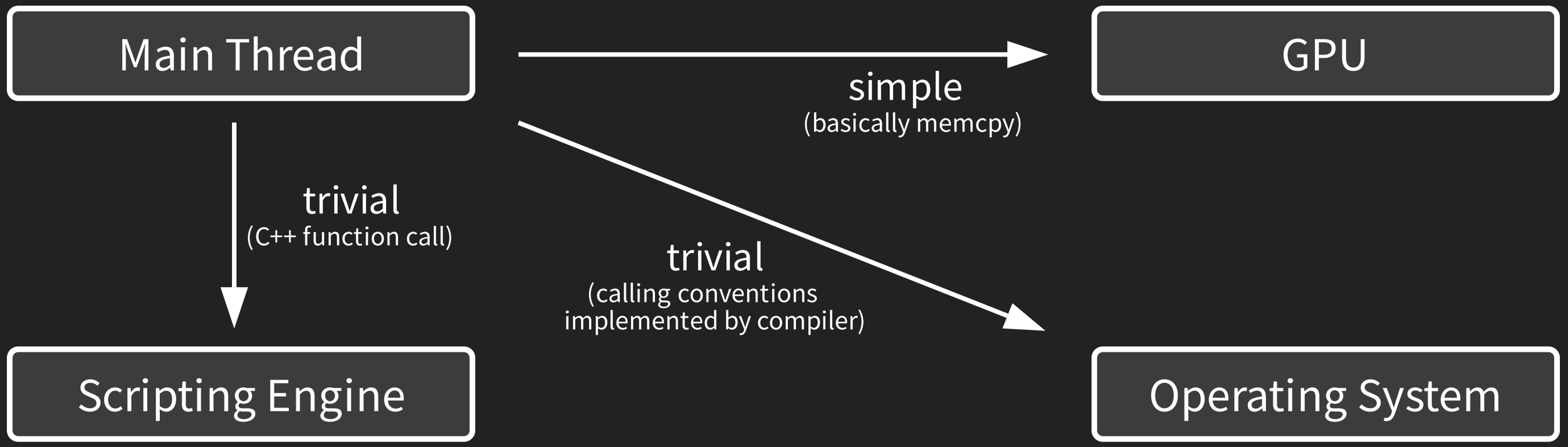
Hardware

Module B

Operating System

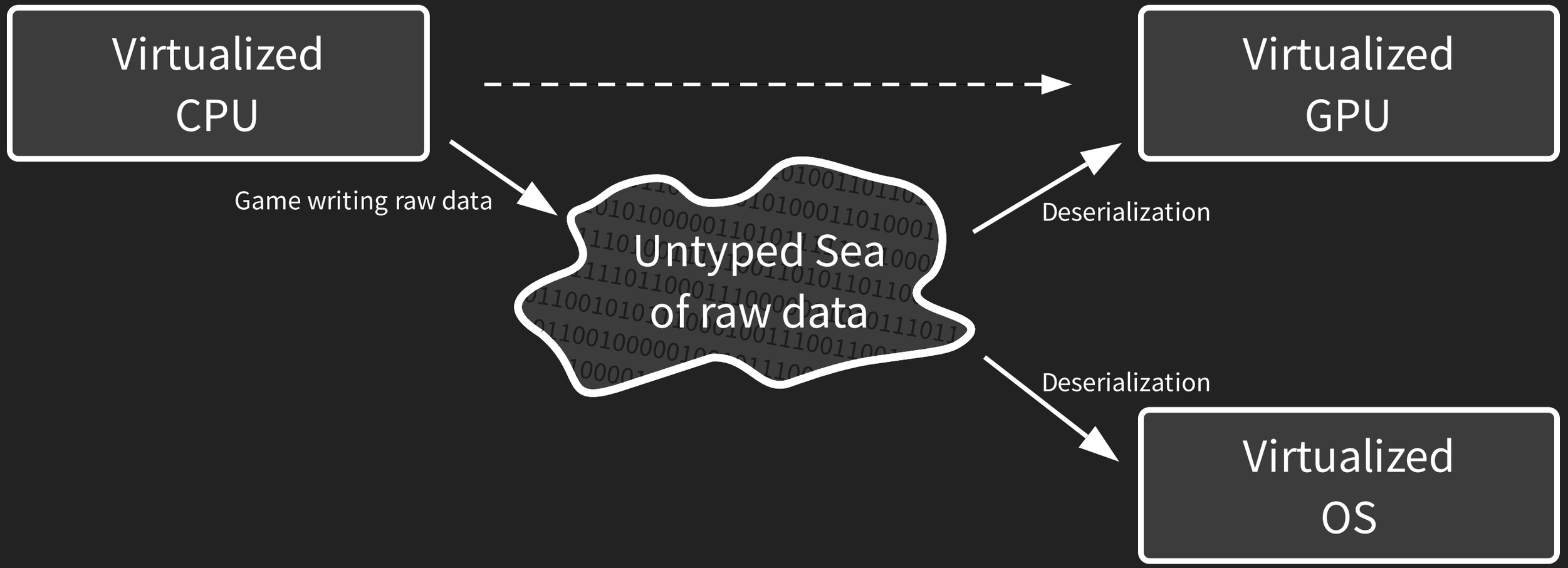
EMULATION & SERIALIZATION

Games:



EMULATION & SERIALIZATION

Emulated Games:



SERIALIZATION & EMULATION

Examples:

- System Calls: CPU registers ⟶ C++ function
- IPC: Memory ⟶ C++ function
- Emulated file IO: Memory ⟶ C++ struct
- GPU command buffers & driver command queues

How to do this reliably?

- Avoid repetitive boilerplate
- Validate inputs and consistency (more boilerplate)
- Detect invalid states in the emulated system

Today's goal: Let the compiler deal with it!

EMULATION & SERIALIZATION

Example: System Call Emulation on ARM32

Virtual CPU

Register	Value
r0	0x1800600
r1	5
r2	0x1ff02000
r3	12
r4	0x200
…	

svc 0x55 ⟶

Virtual Operating System

```
auto [result,dma] = SvcStartDma(LookupHandle(5),
                                0x1ff02000,
                                LookupHandle(12),
                                0x1800600,
                                0x200)
```

Presented at C++::London:
Generative Programming in Action: Emulating the 3DS

THE NINTENDO 3DS

THE NINTENDO 3DS

- Released in 2011
- 2 CPU cores: ARMv6 @ 268 MHz
- Unique-ish GPU (DMP PICA200)
- 128 MB FCRAM
- Software stack:
  - Microkernel (fully multitasking)
  - About 40 microservices
  - Games (+ web browser)

THE 3DS SOFTWARE STACK

Game/Browser	Runs on emulated CPU
Services	API emulation (or could run on emulated CPU)
Kernel: Horizon	API emulation
ARM11 CPUs	Interpreter

INTERPROCESS COMMUNICATION

INTERPROCESS COMMUNICATION

IPC is crucial to everything:

- Rendering graphics (gsp) & playing audio (dsp)
- Accessing WiFi (soc) & connecting to friends (frd)
- Loading assets & saving progress (fs)
- …

~40 processes ("services") in total,
each serving different functionality

IPC PROTOCOL

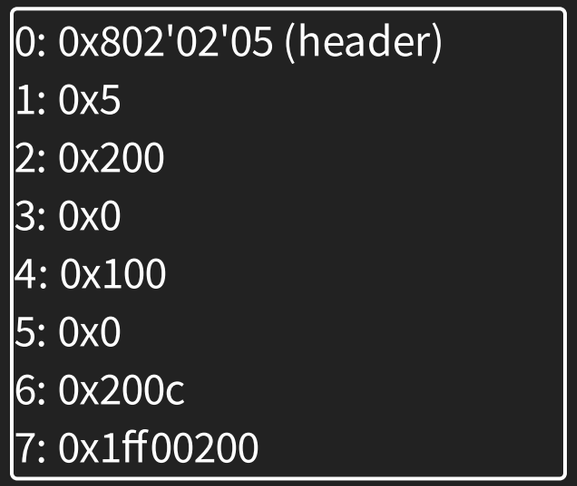
- Client-Server based: Games ⇄ Services
- Request-response exchange via command blocks
- Marshalling of sensitive data by the OS kernel
- Hierarchy of abstraction for exploit mitigation

IPC VISUALIZED

App: ReadFile

Kernel

Service



IPC VISUALIZED

App: ReadFile

```
0: 0x802'02'05 (header)
1: 0x5
2: 0x200
3: 0x0
4: 0x100
5: 0x0
6: 0x200c
7: 0x1ff00200
```

Kernel

```
0: 0x802'02'05
1: 0x5
2: 0x200
3: 0x0
4: 0x100
5: 0x0
6: 0x200c
7: 0x2a700200
```

Service

Translate command block …

IPC VISUALIZED

App: ReadFile

Kernel

Service

… and send it to the service

EMULATING IPC COMMAND HANDLERS

Common structure on handler dispatch:

- Select C++ handler function based on command index

```
std::tuple<Result,uint32_t> DoReadFile(uint32_t, uint64_t, uint64_t, BufferPointerW)
```

- Verify command header (number of parameters)

```
(cmd_header & 0xFF == 5)  &&  ((cmd_header >> 8) & 0xff == 2)
```

- Parse parameters from command block

header 0x8020205	uint32 5	uint64_lo 0xdeadbeef	uint64_hi 0x5555	uint64_lo 0xd00f	uint64_hi 0	buffer descriptor …	buffer addr 0x1ff00200

- Invoke C++ handler function

```
DoReadFile(5, 0x5555deadbeef, 0xd00f, BufferPointerW{0x1ff00200});
```

- Write response back to command block

header: 0x8020002	Result: 0x0	Result 2: 0xd00f

EMULATING IPC COMMAND HANDLERS

How often do we need to write this logic?

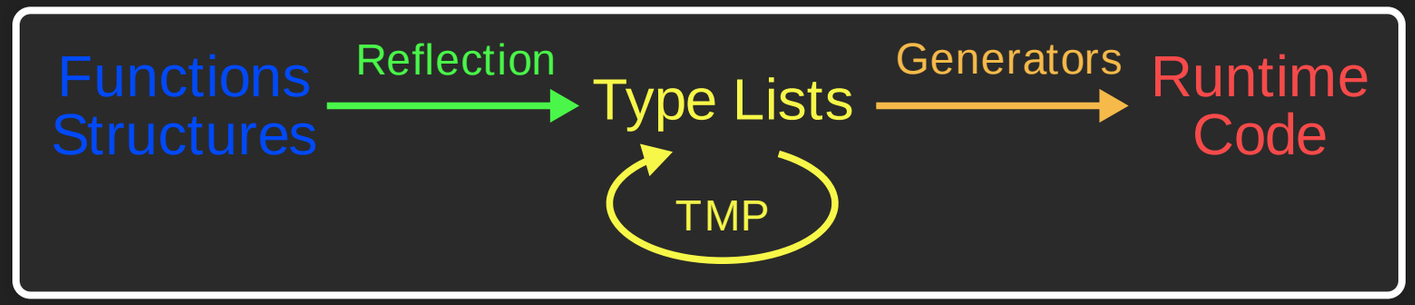
- ~40 active processes
- Each with ~30 IPC commands on average
- Manual glue to invoke the C++ handler required for each

That is a lot of work. Or is it?

Enter Generative Programming

GENERATIVE PROGRAMMING

BUILDING BLOCKS



OUR VISION

```
std::tuple<Result, uint32_t>
DoReadFile(uint32_t file_descriptor, uint64_t offset,
           uint64_t num_bytes, WriteableBuffer& output)
```

↓ Function Traits ↓

```
using RequestList  = std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer>
using ResponseList = std::tuple<Result, uint32_t>
```

↓ Generators ↓

```
template<typename... T> tuple<T...> DecodeMessage(CmdBlock&)
template<typename... T> void        EncodeMessage(CmdBlock&, T... data)
```

↓ Combine ↓

```
GlueCommandHandler(cmd_block, DoReadFile)
```

FUNCTION TRAITS

- Function traits:
  - Type traits for functions
  - Get parameter list & return type

```
template<typename F>
struct FunctionTraits {
  using Args   = std::tuple< /* Parameter list of F */ >;
  using Result = /* Return type of F */;
};
```

Implementations available in

- Boost.FunctionTypes (C++98?)
- Boost.CallableTraits (C++11)

  Standalone: https://github.com/badair/callable_traits

FUNCTION TRAITS

Minimal implementation

```
template<typename F>
struct FunctionTraits;

// Specialize for free functions
template<typename FuncResult, typename... FuncArgs>
struct FunctionTraits<Result(Args...)> {
  using Args   = std::tuple<FuncArgs...>;
  using Result = FuncResult; // NB: This will be some tuple<> for us
};
```

Very limited, but good enough here

GENERATORS

Core idea: Generate runtime code based on a type list via

- Recursion
- `for_each(tuple, f)`
- parameter pack expansions (C++11)
- fold expressions (C++17)

We got our type list from FunctionTraits

How do we generate a command block decoder?

GENERATORS

```
std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer >
```

header 0x8020205	uint32 5	uint64_lo 0xdeadbeef	uint64_hi 0x5555	uint64_lo 0xd00f	uint64_hi 0	buffer descriptor ...	buffer addr 0x1ff00200

```
template<typename TypeList> struct DecodeAllAndApply;

template<typename... Ts>
struct DecodeAllAndApply<std::tuple<Ts...>> {
  uint32_t offset = 0x1; // offset into command block

  // Read a single entry from the CmdBlock and advance "offset"
  template<typename T>
  auto DecodeEntry(CmdBlock& block) { ... }

  // Iterate the entire CmdBlock, gather results and apply to "f"
  template<typename Handler>
  auto operator()(CmdBlock& cmd_block, Handler&& handler) {
    return handler(DecodeEntry<Ts>(cmd_block)... );
  }
};
```

GENERATORS

```
std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer >
```

header 0x8020205	uint32 5	uint64_lo 0xdeadbeef	uint64_hi 0x5555	uint64_lo 0xd00f	uint64_hi 0	buffer descriptor ...	buffer addr 0x1ff00200

Decoding 32-bit values:

```
template<typename... Ts>
struct DecodeAllAndApply<std::tuple<Ts...>> {
  uint32_t offset = 0x1; // offset into command block

  template<typename T>
  auto DecodeEntry(CmdBlock& block) {
    if constexpr (std::is_same_v<T, uint32_t>) {
      return block.ReadU32(offset++);
    } else {
      ...
    }
  }
};
```

GENERATORS

```
std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer >
```

header 0x8020205	uint32 5	uint64_lo 0xdeadbeef	uint64_hi 0x5555	uint64_lo 0xd00f	uint64_hi 0	buffer descriptor ...	buffer addr 0x1ff00200

Decoding 64-bit values:

```
template<typename... T>
struct DecodeAllAndApply<std::tuple<Ts...>> {
  uint32_t offset = 0x1; // offset into command block

  template<typename T>
  auto DecodeEntry(CmdBlock& block) {
    // ...
    } else if constexpr (std::is_same_v<T, uint64_t>) {
      uint32_t val_low  = block.ReadU32(offset++);
      uint32_t val_high = block.ReadU32(offset++);
      return (val_high << 32) | val_low;
    } else {
      ...
    }
  }
};
```

GENERATORS

```
std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer >
```

header 0x8020205	uint32 5	uint64_lo 0xdeadbeef	uint64_hi 0x5555	uint64_lo 0xd00f	uint64_hi 0	buffer descriptor ...	buffer addr 0x1ff00200

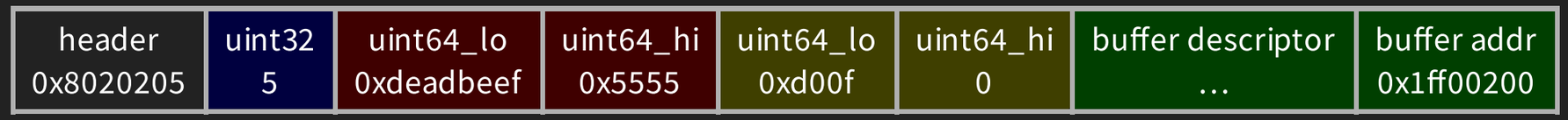
Decoding buffer descriptors:

```
template<typename... T>
struct DecodeAllAndApply<std::tuple<Ts...>> {
  uint32_t offset = 0x1; // offset into command block

  template<typename T>
  auto DecodeEntry(CmdBlock& block) {
    // ...
    } else if constexpr (std::is_same_v<T, WriteableBuffer>) {
      uint32_t descriptor = block.ReadU32(offset++);
      auto [size, flags] = DecodeBufferDescriptor(descriptor);
      uint32_t address = block.ReadU32(offset++);
      return WriteableBuffer { address, size };
    } else {
      ...
    }
  }
};
```

GENERATORS:

```
std::tuple<uint32_t, uint64_t, uint64_t, WriteableBuffer >
```




```
template<typename TypeList> struct DecodeAllAndApply;

template<typename... Ts>
struct DecodeAllAndApply<std::tuple<Ts...>> {
  uint32_t offset = 0x1; // offset into command block

  // Read a single entry from the CmdBlock and advance "offset"
  template<typename T>
  auto DecodeEntry(CmdBlock& block) { ... }

  // Iterate the entire CmdBlock, gather results and apply to "f"
  template<typename Handler>
  auto operator()(CmdBlock& cmd_block, Handler&& handler) {
    // FIXME: Execution order undefined :(
    return handler(DecodeEntry<Ts>(cmd_block)... );
  }
};
```

GENERATORS:

DEMO TIME!

generators.cpp

magic.hpp

GENERATORS: RESULT ENCODER

header 0x8020002	Result 0x0	uint32_t 0xd00f

Trivial with fold expressions!

```
template<typename TypeList> struct EncodeAll;

template<typename... Ts>
struct EncodeAll<std::tuple<Ts...>> {
  uint32_t offset = 0x1;

  template<typename T>
  void EncodeEntry(CmdBlock& block, T t) { ... }

  void operator()(CmdBlock& cmd_block, Ts... ts) {
    (EncodeEntry<T>(cmd_block, ts), ...);
  }
};
```

PUTTING THINGS TOGETHER

```
GlueCommandHandler(DoReadFile, cmd_block);
```

```
template<typename Handler>
void GlueCommandHandler(Handler&& handler, CmdBlock& cmd_block) {
  auto request_header = cmd_block.ReadU32(0);
  using RequestList = typename FunctionTraits<Handler>::Args;
  using ResponseList = typename FunctionTraits<Handler>::Result;
  auto results = DecodeAllAndApply<RequestList>{}(cmd_block, handler);
  cmd_block.WriteU32(BuildResponseHeader(results));
  EncodeAll<ResponseList>{}(cmd_block, results);
}
```

Omitted for now:

- Command header verification
- BuildResponseHeader

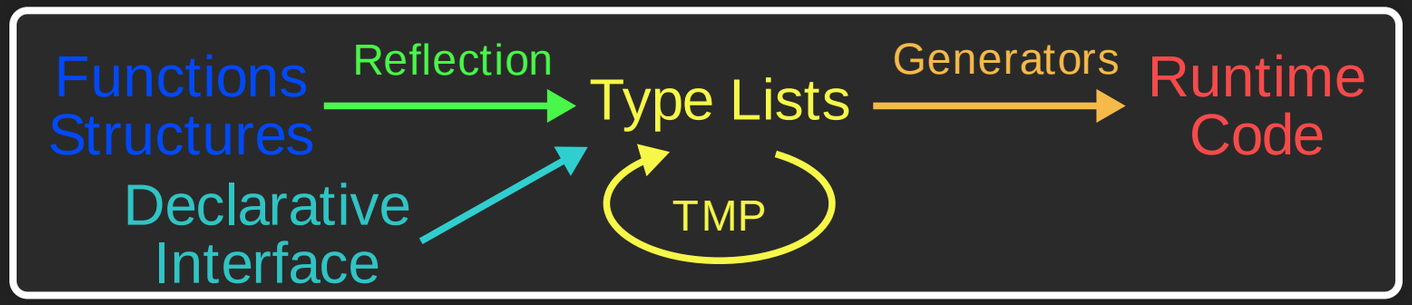
But: This can be used for all IPC commands!

</REFLECTIVE_GENERATORS>

<DECLARATIVE_GENERATORS>

DECLARATIVE COMPILE-TIME PROGRAMMING

Building blocks:



IPC COMMANDS

Need command id + four different type lists:

- Value-based "normal" parameters (simple copy)
- Special parameters (require preprocessing/translation)
- Normal and Special parameters for the response

E.g. FS::OpenFile:

- Request takes `IOFlags`, `FileAttributes`, and `uint32_t`, but also
- Request takes a `StaticBuffer`
- Response gives a `FileDescriptor`, and
- Response gives no special parameters

A DECLARATIVE INTERFACE

```
template<uint32_t CommandId>
struct IPCCmd {
  template<typename... NormalParams>
  struct normal {
    template<typename... SpecialParams>
    struct special {
      // Export template params in the interface
      static constexpr uint32_t command_id = CommandId;
      using normal_params    = std::tuple<NormalParams...>;
      using special_params   = std::tuple<SpecialParams...>;
    };
  };
};

namespace FS { // FileSystem-related commands
using OpenFile    = IPCCmd<0x802>
                  ::normal<IOFlags, FileAttributes, uint32_t>
                  ::special<StaticBuffer>;
using GetFileSize = IPCCmd<0x804>
                  ::normal<FileDescriptor>
                  ::special<>;
}
```

A DECLARATIVE INTERFACE

Adding IPC response layout information is trivial:

```
template<uint32_t CommandId>
struct IPCCmd {
  template<typename... NormalParams>
  struct normal {
    template<typename... SpecialParams>
    struct special {
      template<typename... ResponseNormalParams>
      struct response {
        // Export template params in the interface
        static constexpr uint32_t command_id = CommandId;
        using normal_params           = std::tuple<NormalParams...>;
        using special_params          = std::tuple<SpecialParams...>;
        using response_normal_params  = std::tuple<ResponseNormalParams...>;
};};};};};

namespace FS {
using GetFileSize = IPCCmd<0x804>
                  ::normal<FileDescriptor>::special<>
                  ::response<uint64_t>;
// ...
}
```

A DECLARATIVE INTERFACE

```
using GetFileSize = IPCCmd<0x804>
                    ::normal<FileDescriptor>::special<>
                    ::response<uint64_t>;
```

Builder-like pattern:

- More expressive than plain type lists
- Enforcement of type ordering constraints
- Can handle multiple parameter packs
- Easy to extend interface to include more information

Declarative anatomy of the full IPC command structure!

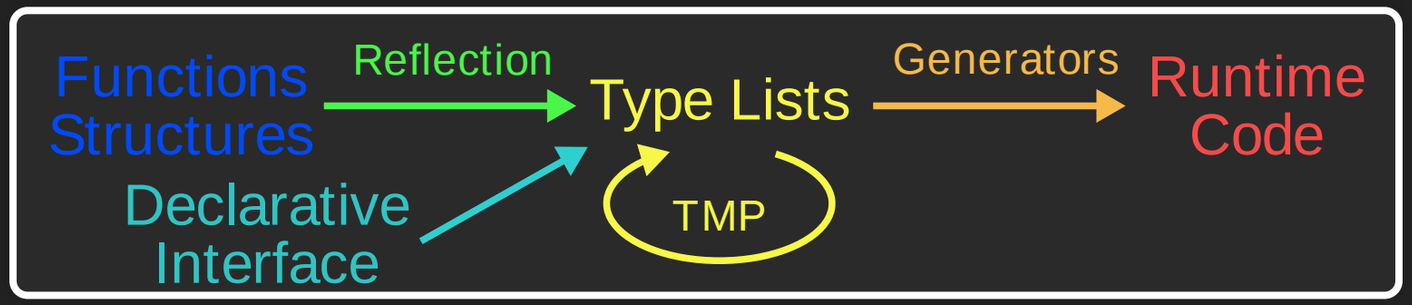
GENERATORS WITH DECLARATIVE INTERFACES

```
template<typename IPCRequest, typename Handler>
void GlueCommandHandler(Handler&& handler, CmdBlock& cmd_block) {
  auto request_header = cmd_block.ReadU32(0);
  if (request_header != IPCRequest::request_header)
    throw std::runtime_error("Invalid request header");

  auto results = DecodeAllAndApply<IPCRequest::request_list>{}(cmd_block, handler);
  cmd_block.WriteU32(IPCRequest::response_header);
  WriteFold<ResponseList>{cmd_block}.Run(results);
}
```

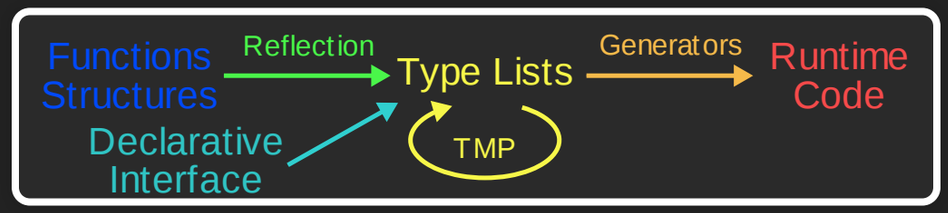
DECLARATIVE COMPILE-TIME PROGRAMMING

Building blocks:



CONCLUSION

- Untyped data makes serialization centric to emulation
- Generating code via stateful variadic folds over type lists
  Fold expressions are big for simplicity!
- Reflection to synthesize code from data structures
  We have function traits now, full reflection in C++2n?
- Declarative interface for maximizing reuse



- Vastly more maintainable and expressive at zero overhead

THX && FAQ ? OK : EOF

neobrain.github.io

@fail_cluez

neobrain