The LLVM Offloading Infrastructure

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together we advance_

Introduction — Offloading

- LLVM Utilities to run programs on external accelerators (GPUs)
- Generic and re-usable between languages and vendors
- Offloading infrastructure has many parts
  - Clang Driver
  - Language frontends
  - Language headers
  - Target backends
  - Binary utilities / formats
  - Device runtimes
  - Offloading runtimes
  - MLIR dialects

Introduction — GPU Compute

- You can run DOOM on it

Offloading Compilation

Compilation — Direct Targets

- Accelerators are just **cross-compiling** targets
  - Supported with the **--target=** option
- Clang driver decides the steps necessary to get a **usable executable**
- Everything should work like the targets you know and love
  - LLVM backends and tools
- *If you omit the CPU and emit LTO IR you can get quasi-generic libraries like SPIR-V*

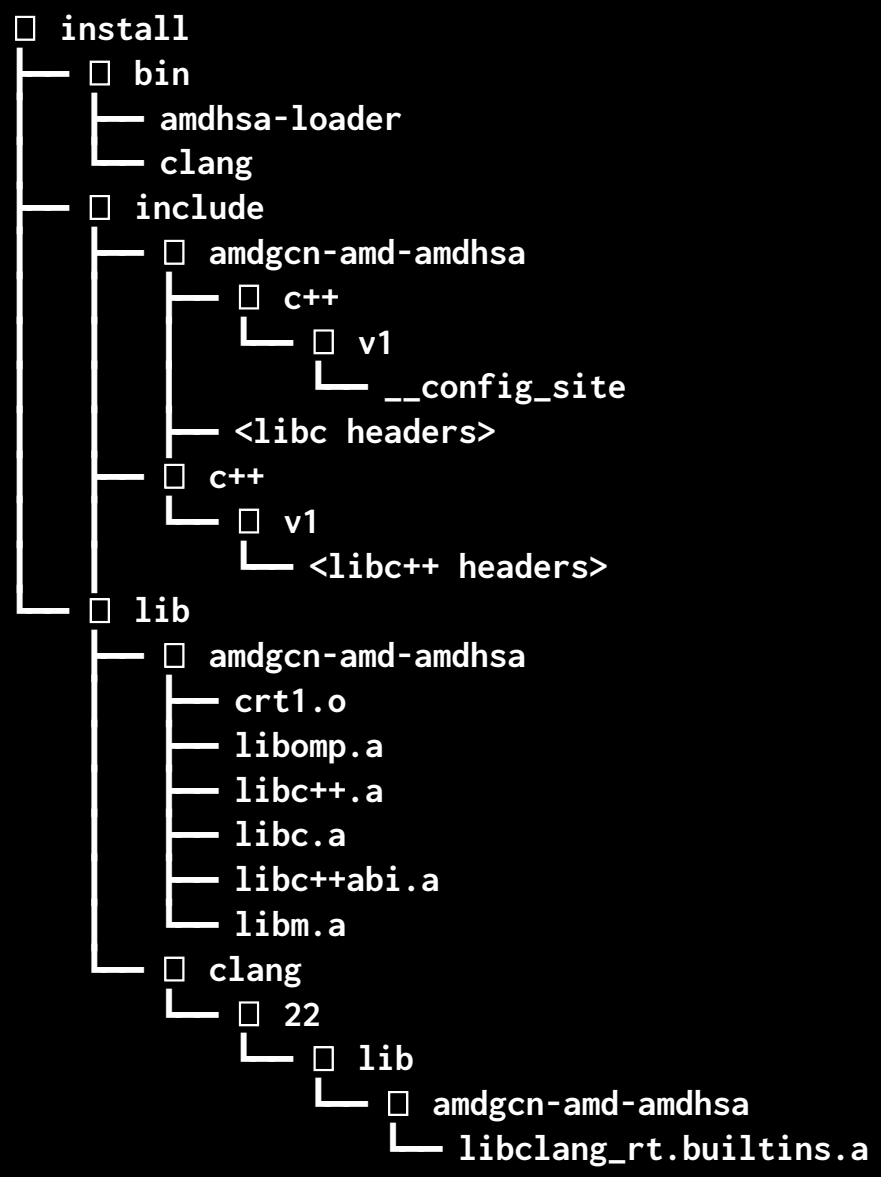
```
#include <gpuintrin.h>
__gpu_kernel void saxpy(int n, float a, float *x, float *y) {
    int i = __gpu_block_id(0) * __gpu_num_blocks(0) + __gpu_thread_id(0);
    if (i < n) y[i] = a * x[i] + y[i];
}
```

```
$ clang kernel.c --target=amdgcn-amd-amdhsa -mcpu=gfx942 -flto
$ clang kernel.c --target=spirv64-- -flto // Work in progress
$ clang kernel.c --target=nvptx64-nvidia-cuda -march=sm_90 -flto
```

Compilation — Runtime Libraries

- Each target gets its own directory
  - `-DLLVM_ENABLE_PER_TARGET_RUNTIME_DIR=ON`
  - `-DLLVM_RUNTIMES_TARGETS=<triples>`
- Included automatically when linking for the language
- Supported GPU runtimes (See my other talks)
  - compiler-rt
  - openmp
  - libc
  - libc++
  - libc++abi
  - flang-rt

```
$ cmake ../llvm -G Ninja                          \
  -C ../offload/cmake/caches/Offload.cmake \
  -DCMAKE_BUILD_TYPE=<Debug|Release>       \
  -DCMAKE_INSTALL_PREFIX=<PATH>            \
$ ninja install
```



Compilation — Offloading Languages

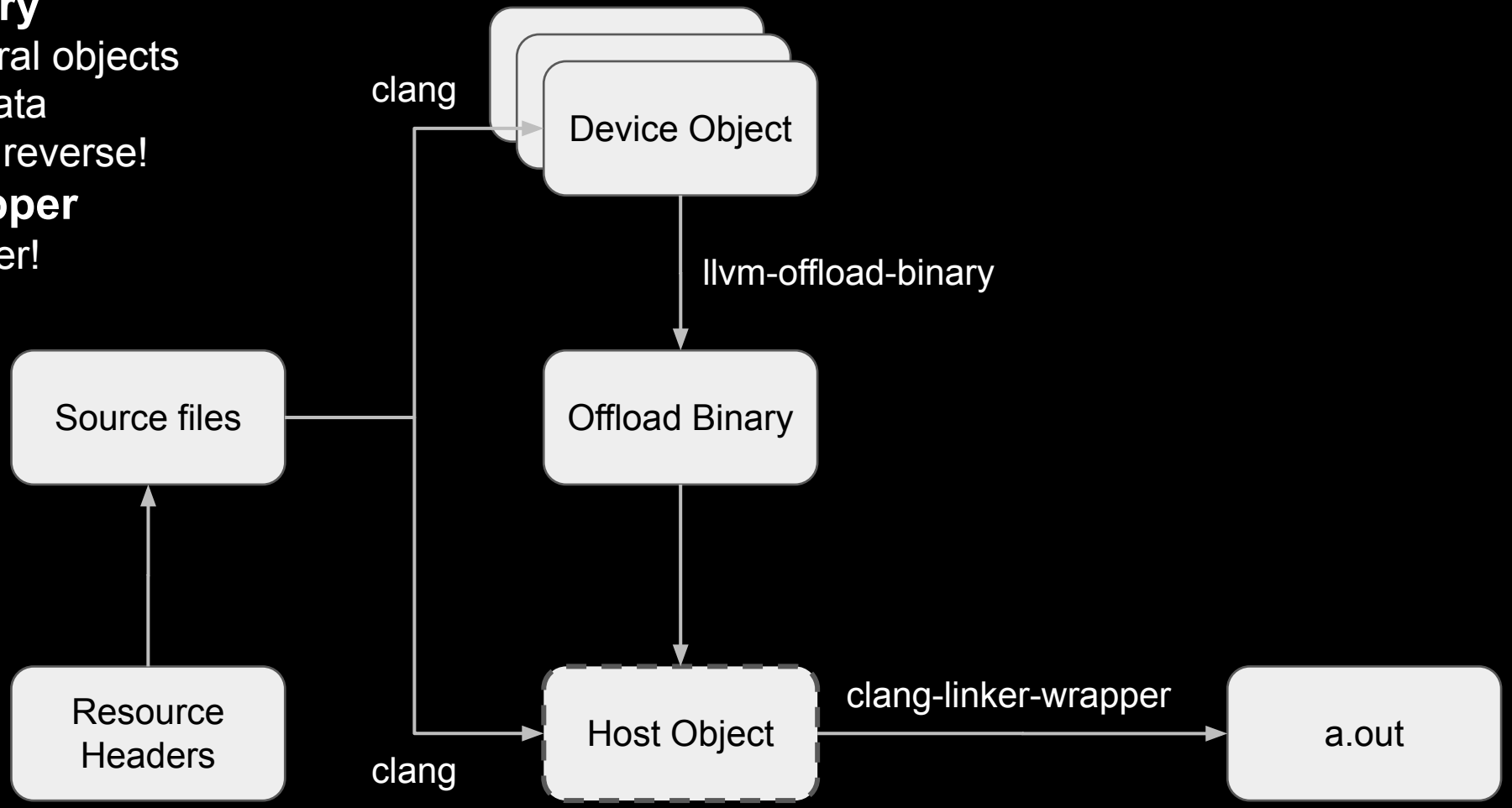
- Ubiquitous for targeting accelerators
  - OpenMP, HIP, SYCL*, CUDA
- Compiler stages managed by the Clang driver toolchain
- Combines **host** and many **device** compilation phases
  - Uses the same core functionality as the standalone case
  - Just some special headers and keywords
- Uses lots of offloading tools under the hood


```
__global__ void saxpy(int n, float a, float *x, float *y) {
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    if (i < n)
        y[i] = a * x[i] + y[i];
}
```

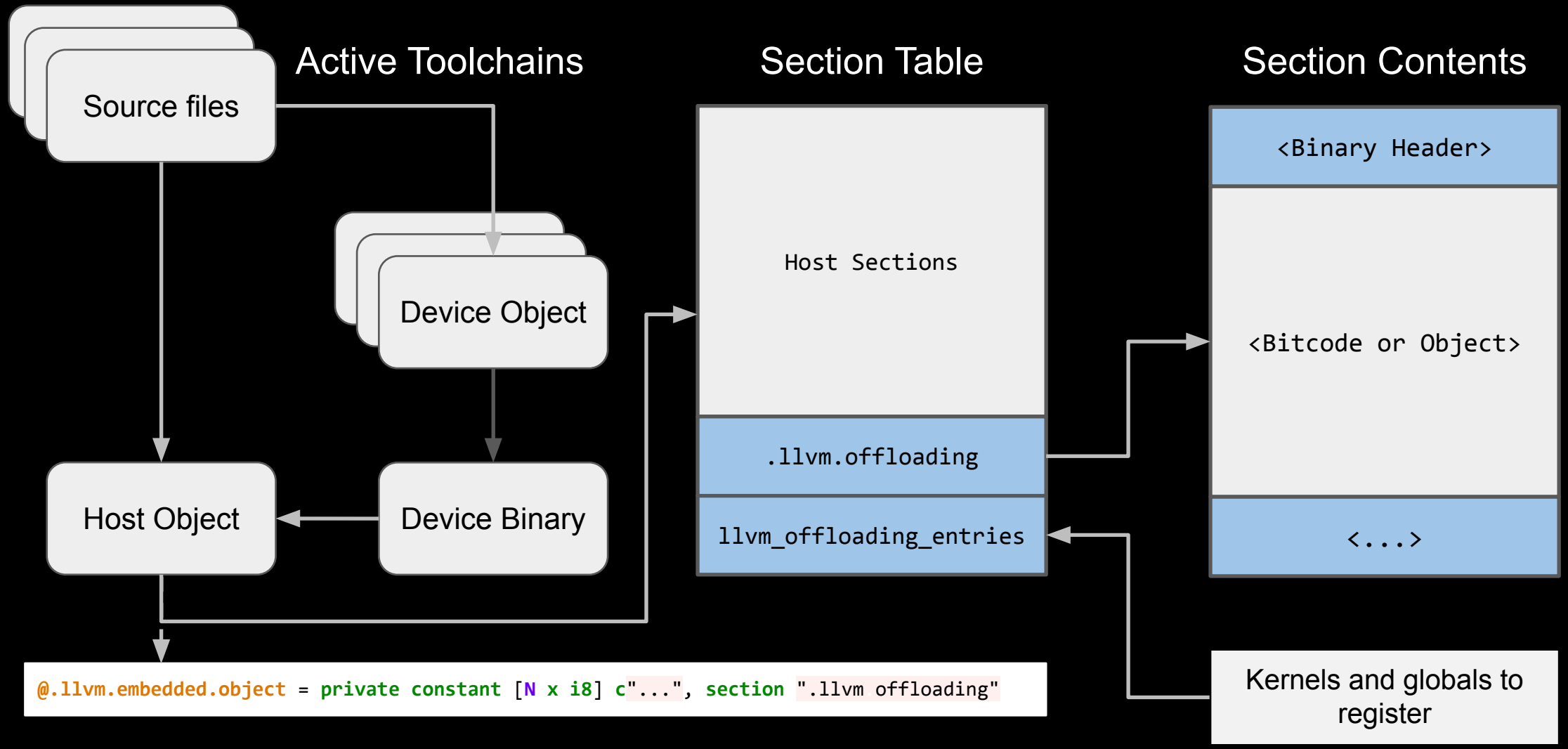
```
$ clang++ -x hip hip.cpp --offload-arch=gfx942 -v
```

Offloading — Compilation Bindings

- **llvm-offload-binary**
  - Combines several objects
  - Includes metadata
  - Can be done in reverse!
- **clang-linker-wrapper**
  - More on this later!



Offloading — Binary Usage



Offloading — Linking

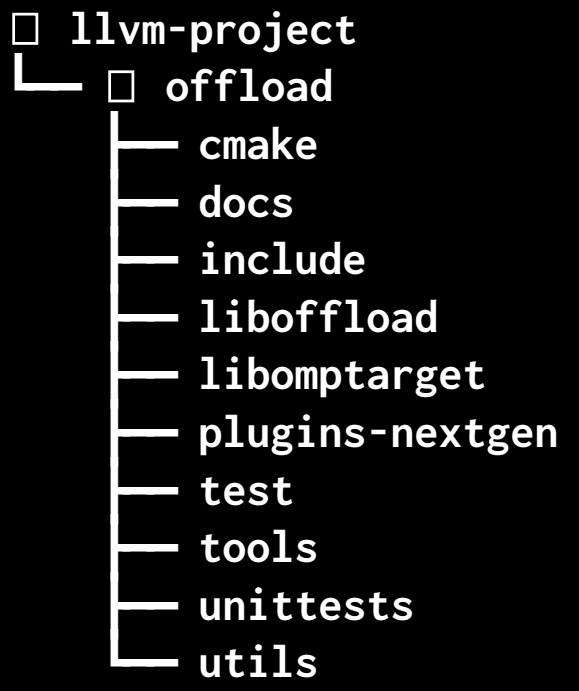
- **clang-linker-wrapper**
  - Performs device linking and runtime call registration in one action
- **llvm-offload-binary**
  - Extracts the files
- **llvm-offload-wrapper**
  - LLVM-IR module that initializes the runtime with the executable
- **llvm-objdump**
  - With **--offloading** will print the contained information

```
$ clang-linker-wrapper host.o --linker-path=/usr/bin/ld.lld
// OR
$ llvm-offload-binary host.o --image=file=dev.o,arch=gfx942
$ clang --target=amdgcn-amd-amdhsa -mcpu=gfx942 dev.o -o image -l<libraries>
$ llvm-offload-wrapper --triple=x86_64-unknown-linux -kind=hip image -o out.bc
$ clang --target=x86_64-unknown-linux out.bc -o reg.o
$ ld.lld host.o reg.o -o a.out
```

Offloading Library / API

Runtime — Project Overview

- The **llvm-project/offload** runtime!
- Generic* interface over vendor GPU runtimes
  - Extensions to keep us from a minimally useful subset
  - Supports AMD, NVIDIA, and Intel* GPUs
    - *Wraps over dynamically opened vendor libraries**
- Originally came from the OpenMP offloading support
  - The libomptarget library
- Made **liboffload** to export it!



OpenMP

Runtime — Liboffload

- Provide a **stable** C API for offloading GPU programs
  - *Aren't there enough of these?*
  - We want ABIs we can control inside LLVM
- **Work-in-progress** still version 0.0 and may change!
- Everything starts with **ol** for **offload library**
  - I vetoed **LLVM offload library**

Runtime — Liboffload Design

- Public interface defined through **tablegen**
  - Automatic documentation
  - Verification and tracing
- Headers installed into **include/offload/OffloadAPI.h***

```
def olInit : Function {
  let desc = "Perform initialization of the Offload library";
  let details = [
    "This must be the first API call made by a user of the Offload library",
    "The underlying platforms are lazily initialized on their first use"
    "Each call will increment an internal reference count that is decremented by `olShutDown`"
  ];
  let params = [];
  let returns = [];
}
```

Runtime — Liboffload Design

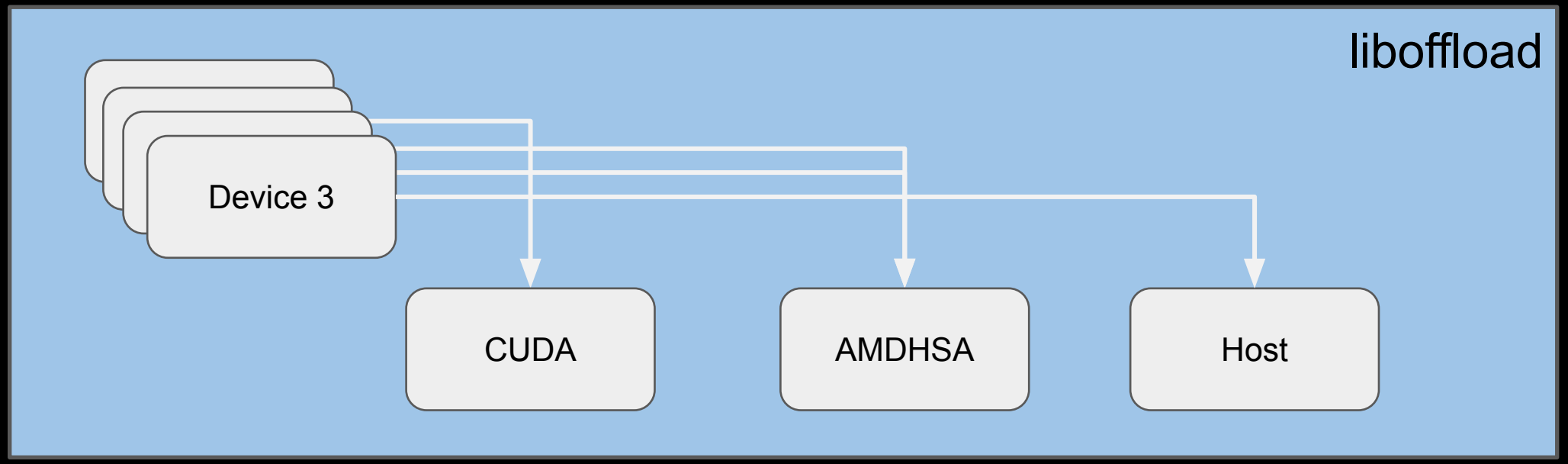
- Generates a public API that calls the internal implementation
- Every API function
  - Returns an error
  - Has a **WithCodeLoc** version for richer error messages

```
OL_APIEXPORT ol_result_t OL_APICALL olInit() {
  if (llvm::offload::isTracingEnabled())
    llvm::errs() << "---> olInit";

  ol_result_t Result = llvmErrorToOffloadError(olInit_impl());

  if (llvm::offload::isTracingEnabled()) {
    llvm::errs() << "()";
    llvm::errs() << "-> " << Result << "\n";
    if (Result && Result->Details)
      llvm::errs() << "     *Error Details* " << Result->Details << " \n";
  }
  return Result;
}
```

```
llvm::Error olInit_impl() { … }
```

Runtime — Liboffload Design

- Objects exposed as **opaque handles**
- Error messages are rich
  - Custom error message
  - Error code
- Exposes **devices** with properties
  - The underlying **platform** is a property of the device



Offloading Example

Example — Compiling an Image

- First we need a GPU program to execute
- Use the direct approach from before
  - Lets use the **libc** library

```c
#include <gpuintrin.h>
#if defined(__AMDGPU__)
const char *platform = "AMDGPU";
#elif defined(__NVPTX__)
const char *platform = "NVPTX";
#endif

__gpu_kernel void kernel(uint32_t x) {
    fprintf(stderr, "Hello from %s thread %d!\n", platform, __gpu_thread_id(0));
}
```

```
$ clang kernel.c --target=amdgcn-amd-amdhsa -mcpu=gfx1030 -lc -flto -o amdgpu
$ clang kernel.c --target=nvptx64-nvidia-cuda -march=sm_89 -lc -flto -o nvptx
```

Example — Initialization

- Load the device image and initialize the runtime

```
#include <offload/OffloadAPI.h>

#define OFFLOAD_ERR(X)                                                  \
  if (ol_result_t Err = X)                                              \
    handleError(Err->Details);

int main(int argc, char **argv) {
  std::vector<char> image = readImage(argv[1]);
  OFFLOAD_ERR(olInit());
  ...
}
```

Example — Device Discovery

- Search for any device that can run our image

```
ol_device_handle_t findDevice(std::vector<char> &binary) {
  ol_device_handle_t Device;
  std::tuple data = std::make_tuple(&Device, &binary);
  OFFLOAD_ERR(olIterateDevices([](ol_device_handle_t Device, void *userData) {
        auto &[output, binary] = *reinterpret_cast<decltype(data)*>(userData);
        bool isValid = false;
        OFFLOAD_ERR(olIsValidBinary(Device, binary->begin(), binary->size(), &isValid));
        if (!isValid) return true; // continue iteration
        *output = Device;
        return false; // found a match
      },
      &data));
  return Device;
```

Example — Program and Queue setup

- Load the image on the discovered device
- Create a queue to push work onto

```
...
ol_device_handle_t device = findDevice(image);

ol_program_handle_t Program;
OFFLOAD_ERR(olCreateProgram(device, image.begin(), image.size(), &Program));

ol_queue_handle_t Queue;
OFFLOAD_ERR(olCreateQueue(device, &Queue));
...
```

Example — Kernel Launch

- Look up the kernel by name
- Push a kernel launch to that symbol

```
  ...
  ol_symbol_handle_t kernel;
  OFFLOAD_ERR(olGetSymbol(Program, "kernel", OL_SYMBOL_KIND_KERNEL, &kernel));

  uint32_t arg = 1;
  ol_kernel_launch_size_args_t launch{1, {1,1,1}, {4,1,1}, 0};
  OFFLOAD_ERR(olLaunchKernel(Queue, device, kernel, &arg, sizeof(arg), &launch));

  OFFLOAD_ERR(olSyncQueue(Queue));
  OFFLOAD_ERR(olDestroyQueue(Queue));
  OFFLOAD_ERR(olDestroyProgram(Program));
  OFFLOAD_ERR(olShutDown());
}
```

Example — Compile and run

- Now you too can run random programs on your GPU!
  - A small version of **llvm-gpu-loader** I use for tests

```
$ clang++ my_offload_program.cpp -I<install>/include -lLLVMOffload -o offload
$ ./offload amdgpu
Hello from AMDGPU thread 0!
Hello from AMDGPU thread 1!
Hello from AMDGPU thread 2!
Hello from AMDGPU thread 3!
$ ./offload nvptx
Hello from NVPTX thread 0!
Hello from NVPTX thread 1!
Hello from NVPTX thread 2!
Hello from NVPTX thread 3!
```

Conclusion — Future Work

- SPIR-V
  - Need to create a SPIR-V version of **<gpuintrin.h>**
  - Needs support in the runtime
- MLIR
  - Should have an **liboffload** target like we have for HIP and CUDA
- API
  - Needs fine-grained initialization options
  - Split **libomptarget** from **offload** entirely
  - Need to finalize the API!
- Reach out if you’re interested in using or contributing!

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