A C/C++ Toolchain for your GPU

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Introduction — GPGPU

- Modern GPUs have evolved into general purpose accelerators
- Provide a C/C++ toolchain that runs on the GPU
  - Trivially port applications to run on the GPU
  - Generic implementations of math / utility functions
  - Run unit tests on the GPU
  - It’s also fun
- How to port the existing C/C++ libraries to the GPU?
  - Lots of existing options

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Targeting GPUs — CUDA / HIP

- Ubiquitous for targeting GPUs
- GPU code is manually declared
  - **`__global__`** and **`__device__`**
- Difficult to integrate into existing build systems
  - One compile job yields many files
  - Host and device compilations must both compile
- Less portable
- Compiled by the clang frontend
- Runtime implemented by builtins

NVIDIA CUDA

```
__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=gfx940 -###
-cc1 -triple amdgcn-amd-amdhsa … -fcuda-is-device -x hip
```

```
#include "device_amd_hsa.h" // HIP Runtime

ATTR size_t __ockl_get_local_id(uint dim) {
  switch (dim) {
  case 0: return __builtin_amdgcn_workitem_id_x();
  case 1: return __builtin_amdgcn_workitem_id_y();
  case 2: return __builtin_amdgcn_workitem_id_z();
  }
}
```

Targeting GPUs — OpenMP

- Uses C++ with compiler **pragmas**
  - **`#pragma omp declare target`**
- More "standard" C++
- Same issues with build systems
- Very portable
- Compiled by the clang frontend
- Uses the **same** builtins for the runtime

```
void saxpy(int n, float a, float *x, float *y) {
    #pragma omp target teams distribute parallel for
    for (int i = 0; i < n; ++i)
        y[i] = a * x[i] + y[i];
}
```

```
$ clang++ -x cpp openmp.cpp -fopenmp --offload-arch=gfx940 -###
-cc1 -triple amdgcn-amd-amdhsa … -fopenmp-is-target-device
```

```
#include <Mapping.h> // OpenMP Runtime

uint32_t getThreadIdInBlock(int32_t Dim) {
  switch (Dim) {
  case 0: return __builtin_amdgcn_workitem_id_x();
  case 1: return __builtin_amdgcn_workitem_id_y();
  case 2: return __builtin_amdgcn_workitem_id_z();
  }
}
```

Targeting GPUs — OpenCL

- Uses a more conventional approach
  - Easier to fit into existing builds
- OpenCL is fundamentally limited
  - No function pointers
  - No recursion
  - Conflicting definitions of C functions
  - OpenCLC++ has templates at least
- Also compiled through the clang frontend
- The runtime uses the **same** builtin functions
  - You get the idea

```
__kernel void
saxpy(int n, float a, __global float* x, __global float* y) {
    int i = get_global_id(0);
    if (i < n) y[i] = a * x[i] + y[i];
}
```

```
$ clang++ -x cl opencl.cl --target=amdgcn-- -mcpu=gfx940
-cc1 -triple amdgcn-amd-amdhsa … -x cl
```

```
#include <clc/clc.h> // OpenCL Runtime

_CLC_DEF _CLC_OVERLOAD size_t get_local_id(uint dim) {
  switch (dim) {
  case 0: return __builtin_amdgcn_workitem_id_x();
  case 1: return __builtin_amdgcn_workitem_id_y();
  case 2: return __builtin_amdgcn_workitem_id_z();
  }
}
```

Targeting GPUs — C/C++

- Why bother porting anything in the first place?
- All of these languages are just different versions of **clang**
  - We can just target C/C++ directly without a GPU language
- Use **`--target=amdgcn-amd-amdhsa`** to invoke the clang target
- Our linker is **ld.lld** so we can use LTO and static libraries
  - Don’t specify **-mcpu=** and we can get generic LLVM-IR

Targeting GPUs — ISO C/C++

```
void matmul(float *A, float *B, float *C, int N) {
  for (int i = 0; i < N; ++i) {
    for (int j = 0; j < N; ++j) {
      float sum = 0.0;
      for (int k = 0; k < N; ++k)
        sum += A[i * N + k] * B[k * N + j];
      C[i * N + j] = sum;
    }
  }
}
```

Targeting GPUs — C/C++ Extensions

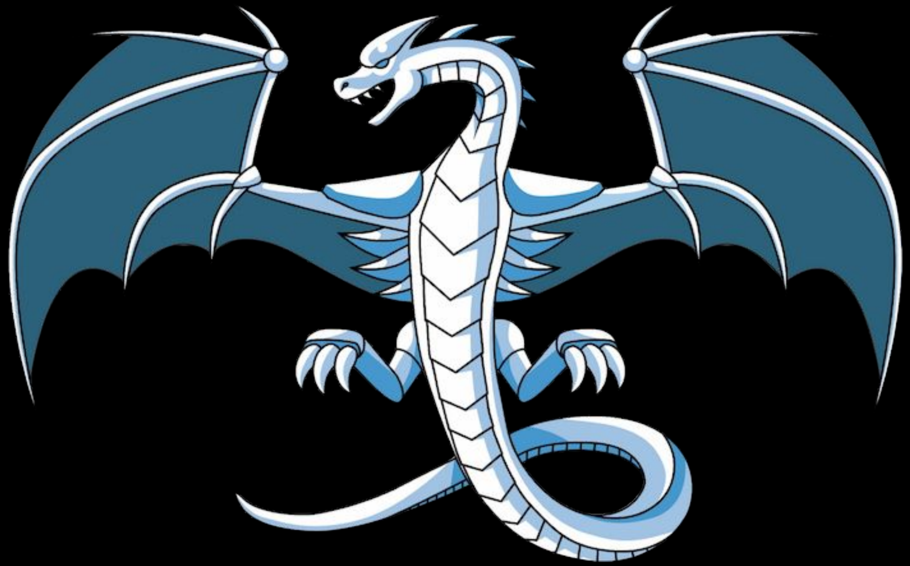
```
[[clang::amdgpu_kernel]] void matmul(float *A, float *B, float *C, int N) { // Target calling convention
  static [[clang::address_space(3)]] float A_s[TILE][TILE]; // Target address space for __shared__
  static [[clang::address_space(3)]] float B_s[TILE][TILE]; // Target address space for __shared__

  int bx = __builtin_amdgcn_workgroup_id_x(); int tx = __builtin_amdgcn_workitem_id_x(); // Builtin functions
  int by = __builtin_amdgcn_workgroup_id_x(); int ty = __builtin_amdgcn_workitem_id_y(); // Builtin functions

  for (int ph = 0; ph < N / TILE; ++ph) {
    A_s[ty][tx] = A[(by * TILE + ty) * N + ph * TILE + tx];
    B_s[ty][tx] = B[(ph * TILE + ty) * N + bx * TILE + tx];
    __builtin_amdgcn_s_barrier(); // Builtin functions
    float sum = 0.0f;
    for (int k = 0; k < TILE; ++k)
      sum += A_s[ty][k] * B_s[k][tx];
    __builtin_amdgcn_s_barrier(); // Builtin functions
  }
  C[(by * TILE + ty) * N + bx * TILE + tx] = sum;
}
```

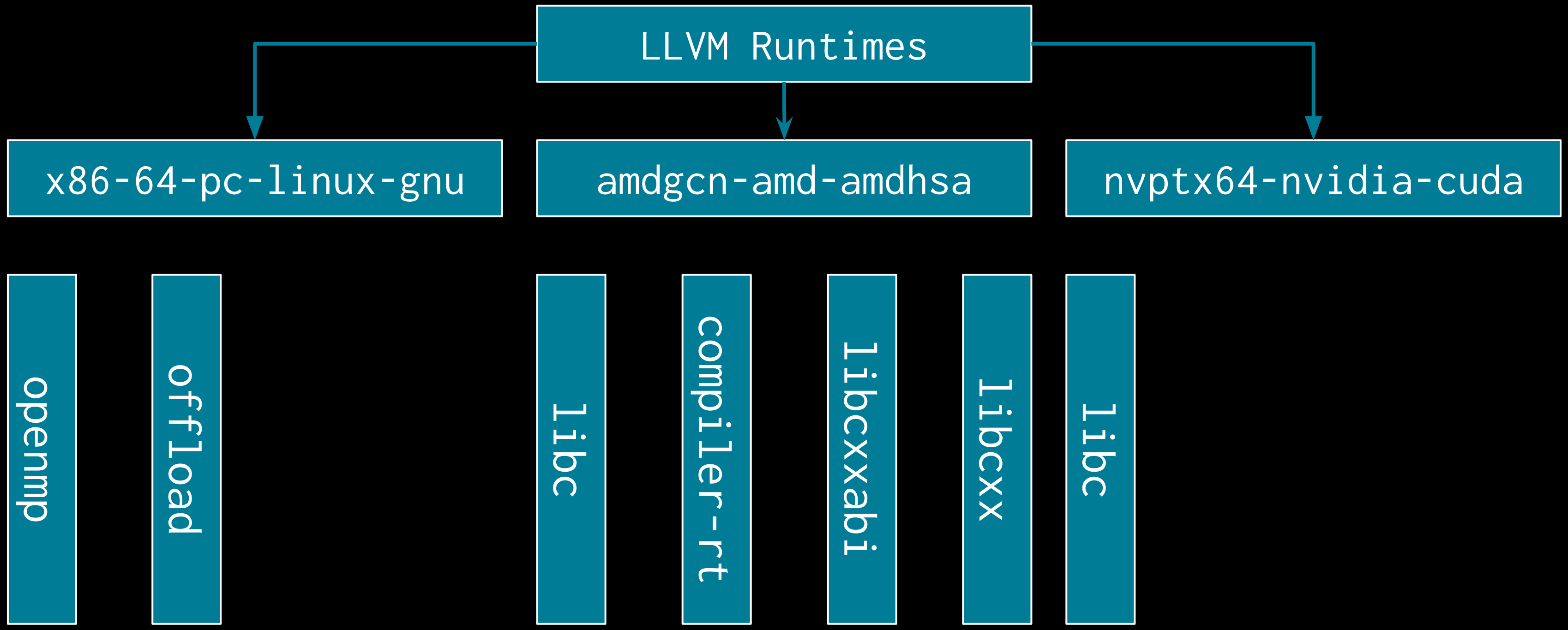
Cross Compiling — C/C++

- This is just cross compiling!
  - Plenty of build systems support this natively
- A complete compiler toolchain has…
  - A compiler frontend ✓
  - An assembler ✓
  - A linker ✓
  - Runtime libraries ✗
- Lets port the LLVM C and C++ runtimes to the GPU!



LLVM Runtimes — Introduction

- Bootstraps multiple libraries using the just-built clang
- Create the libraries for multiple targets
  - -DLLVM_RUNTIME_TARGETS=default;amdgcn-amd-amdhsa;nvptx64-nvidia-cuda
- CMake arguments can be passed individually to each runtime target
  - -DRUNTIMES_<triple>_<var>=<value>



Clang/LLVM — Multilibs

- Each runtime gets its own directory
  - `-DLLVM_ENABLE_PER_TARGET_RUNTIME_DIR=ON`
- Use the GPU target to create the toolchain
- Clang will point to the appropriate folder
  - Only need to pass **-lm -lc …**
- Now let’s actually build them

```
□ install
├── □ bin
│   ├── amdhsa-loader
│   └── clang
├── □ include
│   ├── □ amdgcn-amd-amdhsa
│   │   ├── □ c++
│   │   │   └── □ v1
│   │   │       └── __config_site
│   │   └── <libc headers>
│   └── □ c++
│       └── □ v1
│           └── <libc++ headers>
└── □ lib
    ├── □ amdgcn-amd-amdhsa
    │   ├── crt1.o
    │   ├── libc++.a
    │   ├── libc.a
    │   ├── libc++abi.a
    │   └── libm.a
    └── □ clang
        └── □ 20
            └── □ lib
                └── □ amdgcn-amd-amdhsa
                    └── libclang_rt.builtins.a
```

LLVM Runtimes — LLVM libc

- The C library is the basis of other applications
- The LLVM C library is highly configurable
    - Just enable the functions we want and compile them
- System calls are handled through **Remote Procedure Calls**
    - Client / server protocol communicating through mutual exclusion on unified memory
- See my talk last year for more detailed information
    - **The LLVM C Library for GPUs**

```
set(TARGET_LIBC_ENTRYPOINTS
  …
  # stdio.h entrypoints
  libc.src.stdio.printf
  libc.src.stdio.vprintf
  libc.src.stdio.fprintf
  libc.src.stdio.vfprintf
  libc.src.stdio.snprintf
  libc.src.stdio.sprintf
  libc.src.stdio.vsnprintf
  libc.src.stdio.vsprintf
  libc.src.stdio.asprintf
  libc.src.stdio.vasprintf
  libc.src.stdio.sscanf
  libc.src.stdio.vsscanf
  libc.src.stdio.fscanf
  …
)
```

LLVM Runtimes — LLVM libc

- Make the GPU look like a normal hosted target
- Standard **libc** implementations use a startup object (i.e. **crt1.o**) to call the main function
  - Just write one for the GPU
- Cross compiling emulators run tests
  - Write one for the GPU using the GPU runtime

```
void call_init_callbacks(int argc, char **argv, char **env) {
  /* Call global constructors. */
}

void call_fini_callbacks() { /* Call global destructors. */ }

extern "C" {
[[gnu::visibility("protected"), clang::amdgpu_kernel]] void
_begin(int argc, char **argv, char **env, void *in, void *out)
{
  atexit(&call_fini_callbacks);
  call_init_callbacks(argc, argv, env);
}

[[gnu::visibility("protected"), clang::amdgpu_kernel]] void
_start(int argc, char **argv, char **envp, int *ret) {
  __atomic_fetch_or(ret, main(argc, argv, envp),
                    __ATOMIC_RELAXED);
}

[[gnu::visibility("protected"), clang::amdgpu_kernel]] void
_end(int retval) {
  exit(retval);
}
}
```

LLVM Runtimes — Compiler-RT

- Provides a runtime library that Clang will implicitly call
  - `libclang_rt.builtins.a`
- Porting is very straightforward
  - Just enable the runtimes build and set a few flags
- This gives us a functional C toolchain for the GPU
- Now we can compile some more interesting things for the GPU

```c
#include <stdio.h>

int main(int argc, char **argv) {
  fprintf(stdout, "%s %d\n", argv[0] , __builtin_amdgcn_workgroup_id_x());
}
```

```
$> clang app.c --target=amdgcn-amd-amdhsa -flto -mcpu=native -lc -lm -lclang_rt.builtins crt1.o -nogpulib
$> amdhsa-loader --blocks 3 ./a.out
./a.out 1
./a.out 0
./a.out 2
```

LLVM Runtimes — libc++

- Build the C++ libraries on top of the C toolchain
- Disable some things we can't handle right now
  - Threads and Filesystem support mostly
  - Lots of config options so we provide a cache file
    - `-DRUNTIMES_amdgcn-amd-amdhsa_CACHE_FILES=libcxx/caches/AMDGPU.cmake`
- Other approaches exist but typically require a separate include path

LLVM Runtimes — libc++ example

```cpp
#include <...>

int main(int argc, char **argv) {
  std::mt19937 generator(__builtin_amdgcn_workitem_id_x());
  std::uniform_int_distribution<int> dist(1, 100);

  std::vector<int> vec(8);
  std::ranges::generate(vec, [&]() { return dist(generator); });

  for (int x : vec)
    std::cout << x << " ";
}
```

```
$> clang++ app.cpp --target=amdgcn-amd-amdhsa -flto -mcpu=native -lc -lm -lc++ -lc++abi \
     crt1.o -lclang_rt.builtins -stdlib=libc++ -nogpulib -fno-exceptions
$> amdhsa-loader ./a.out
45 48 65 68 68 10 84 22
```

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LLVM Runtimes — Testing libc++

- libc++ already has support for custom test executors
- We can run the test suite on the GPU for free
  - Found a lot of obscure compiler bugs
- Still a lot of failures but it's a start

```
$> ninja -C
runtimes/runtimes-amdgcn-amd-amdhsa-bins check-cxx

Testing Time: 1092.29s
Total Discovered Tests: 9749
Unsupported   : 2743 (28.14%)
Passed        : 6804 (69.79%)
Expectedly Failed:   48 (0.49%)
Failed        :  154 (1.58%)
```


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LLVM Runtimes — Bringing to Offloading Languages

- Must specify which definitions are available to the device
- We export a static library in the target-specific directory
- Just link it with the device-side compilation, the compiler knows where to find it
  - All these languages use the same linker and toolchain remember?

```
#include <iostream>

#pragma omp declare target to(std::cout)

int main() {
#pragma omp target
  std::cout << "Hello World\n";
}
```

```
$> clang++ hello.cpp -fopenmp --offload-arch=native -Xoffload-linker -lc++ \
     -Xoffload-linker -lc++abi -Xoffload-linker -lc -fno-exceptions -stdlib=libc++
$> ./a.out
Hello World
```

LLVM Runtimes — Bringing it all Together

- We can build a functional C/C++ toolchain that targets the GPU
- The magic spell to summon it

```
$> cd llvm-project  # The llvm-project checkout
$> mkdir build
$> cd build
$> cmake ../llvm -G Ninja                                           \
   -DLLVM_ENABLE_PROJECTS="clang;lld"                               \
   -DCMAKE_BUILD_TYPE=<Debug|Release>   \ # Select build type
   -DCMAKE_INSTALL_PREFIX=<PATH>        \ # Where the libraries will live
   -DRUNTIMES_amdgcn-amd-amdhsa_CACHE_FILES="./libcxx/cmake/caches/AMDGPU.cmake"    \
   -DRUNTIMES_nvptx64-nvidia-cuda_CACHE_FILES="./libcxx/cmake/caches/NVPTX.cmake"   \
   -DRUNTIMES_amdgcn-amd-amdhsa_LLVM_ENABLE_RUNTIMES="libc;compiler-rt;libcxx;libcxxabi"   \
   -DRUNTIMES_nvptx64-nvidia-cuda_LLVM_ENABLE_RUNTIMES="libc;compiler-rt;libcxx;libcxxabi" \
   -DLLVM_RUNTIME_TARGETS="default;amdgcn-amd-amdhsa;nvptx64-nvidia-cuda"
$> ninja install
```

Challenges

- How to handle **<mutex>** and **<thread>**?
  - GPUs have limited forward progress guarantees
  - Cooperative launches can probably help
- Compile times!
  - Really bad because we need LTO for both performance and portability
- HIP/CUDA/OpenMP must compile the same headers on the CPU/GPU
  - Things must be explicitly declared on the GPU
- What if we copy something from the CPU to the GPU?
  - std::vector calls realloc on the GPU, instant segfault
  - std::mutex calls futex, GPU cannot notify the thread
- Not as many useful functions in **libc++**
  - Huge resource requirements when compared to **libc**
- Should we provide exceptions?
- NVIDIA is limited by PTX and nvlink
- …

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Running DOOM on the GPU

https://github.com/jhuber6/doomgeneric

DOOM — Demo

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