# LLVM in HPC

## Enabling Performance Portability, Interoperability, and Novel Features

Johannes Doerfert <jdoerfert@llnl.gov>

Prepared by LLNL under Contract DE-AC52-07NA27344.

# LLVM/OpenMP - A Community Effort

Weekly Meeting: https://bit.ly/2Zqt49v

## “Academia”

- Shilei Tian (SBU)
- Giorgis Georgakoudis (LLNL)
- Michael Kruse (ANL)
- Joachim Protze (RWTH A.)
- Joel Denny (ORNL)
- Atmn Patel (Northwestern)
- Konstantinos Parasyris (LLNL)
- Marc Jasper (LLNL)
- Many, many, more

## Industry

- Joseph Huber (AMD)
- Alexey Bataev (Intel)
- Jon Chesterfield (AMD)
- George Rokos (Intel)
- Pushpinder Singh (AMD)
- Kiran Chandramohan (ARM)
- Chi Chun Chen (HPE/Cray)
- Andrey Churbanov (Intel)
- Carlo Bertolli (AMD)
- Valentin Clement (NVIDIA)
- Many, many, more

## Power Users

- Ye Luo (ANL)
- Christopher Daley (NERSC)
- John Tramm (ANL)
- Rahul Gayatri (NERSC)
- Itaru Kitayama (RIKEN)
- Wael Elwasif (ORNL)
- Tom Scogland (LLNL)
- More that I have forgotten

# About Me

2018 — PhD in CS from Saarland University, Saarbrücken, Germany

Since last week — Researcher at Lawrence Livermore National Laboratory (LLNL) – at ANL before

Active in the LLVM community since 2014, in the OpenMP community since 2018

Me @ ETH

Code owner for OpenMP offloading in LLVM (officially) since 2021

# LLVM

# LLVM in a Nutshell

- open (source/community/...)

- extensible, “fixable”
- portable (GPUs, CPUs, …)
- C++/OpenMP/SYCL/HIP/CUDA/… feature complete😉
- early access to *the coolest* features

- performant and correct ;)

- the basis for most vendor compilers

Thanks 2 Ryan Houdek

[😉 eventually]

C-family frontend (compile C/C++/Cuda/...)

memory, address, UB, thread, ... sanitizers

"modern" Fortran frontend, aka F18 (WIP)

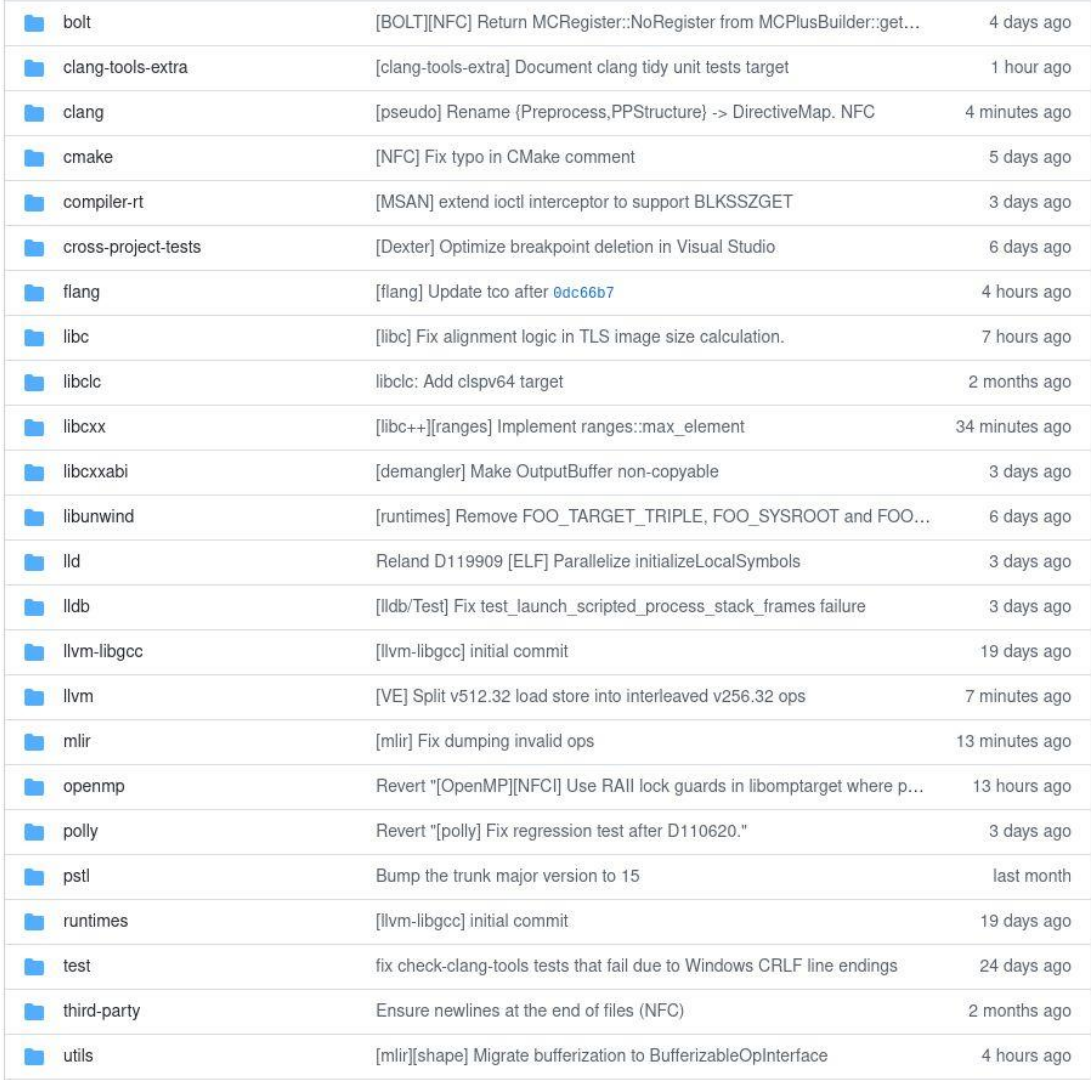
C++ standard library (replaces libstdc++)

"fast" and feature rich linker (replaces ld)

LLVM-centric debugger (replaces gdb)

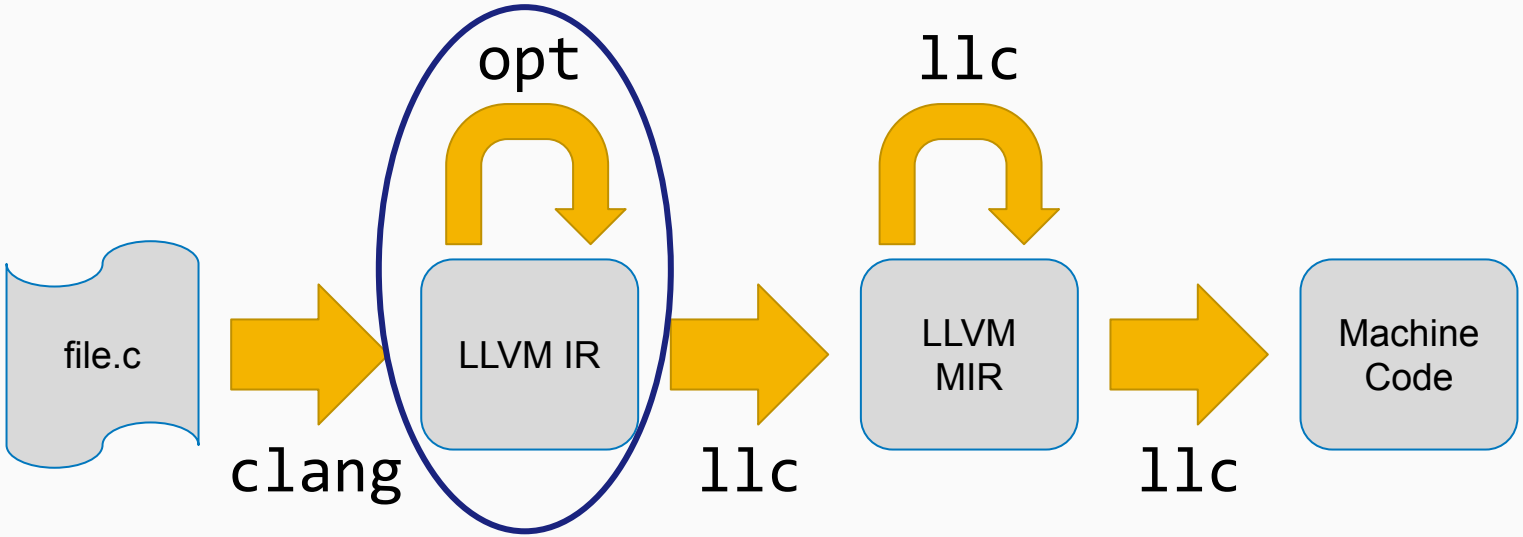
"core-LLVM", middle-end & backends

OpenMP runtimes (host, device, and plugins)



| | | |
|---|---|---|
| bolt | [BOLT][NFC] Return MCRegister::NoRegister from MCPlusBuilder::get... | 4 days ago |
| clang-tools-extra | [clang-tools-extra] Document clang tidy unit tests target | 1 hour ago |
| clang | [pseudo] Rename {Preprocess,PPStructure} -> DirectiveMap. NFC | 4 minutes ago |
| cmake | [NFC] Fix typo in CMake comment | 5 days ago |
| compiler-rt | [MSAN] extend ioctl interceptor to support BLKSSZGET | 3 days ago |
| cross-project-tests | [Dexter] Optimize breakpoint deletion in Visual Studio | 6 days ago |
| flang | [flang] Update tco after 0dc66b7 | 4 hours ago |
| libc | [libc] Fix alignment logic in TLS image size calculation. | 7 hours ago |
| libclc | libclc: Add clspv64 target | 2 months ago |
| libcxx | [libc++][ranges] Implement ranges::max_element | 34 minutes ago |
| libcxxabi | [demangler] Make OutputBuffer non-copyable | 3 days ago |
| libunwind | [runtimes] Remove FOO_TARGET_TRIPLE, FOO_SYSROOT and FOO... | 6 days ago |
| lld | Reland D119909 [ELF] Parallelize initializeLocalSymbols | 3 days ago |
| lldb | [lldb/Test] Fix test_launch_scripted_process_stack_frames failure | 3 days ago |
| llvm-libgcc | [llvm-libgcc] initial commit | 19 days ago |
| llvm | [VE] Split v512.32 load store into interleaved v256.32 ops | 7 minutes ago |
| mlir | [mlir] Fix dumping invalid ops | 13 minutes ago |
| openmp | Revert "[OpenMP][NFCI] Use RAII lock guards in libomptarget where p... | 13 hours ago |
| polly | Revert "[polly] Fix regression test after D110620." | 3 days ago |
| pstl | Bump the trunk major version to 15 | last month |
| runtimes | [llvm-libgcc] initial commit | 19 days ago |
| test | fix check-clang-tools tests that fail due to Windows CRLF line endings | 24 days ago |
| third-party | Ensure newlines at the end of files (NFC) | 2 months ago |
| utils | [mlir][shape] Migrate bufferization to BufferizableOpInterface | 4 hours ago |

# LLVM/Clang 101




Slide originally by *Eric Christopher* and *Johannes Doerfert*

https://youtu.be/J5xExRGaIIY

# Building LLVM

Single command often suffices to configure:

```
cmake …/llvm-project/llvm -DLLVM_ENABLE_PROJECTS='clang' -DLLVM_ENABLE_RUNTIMES=’openmp’
make -j
```

Useful options include:

```
CMAKE_BUILD_TYPE={Release,Asserts,…}
LLVM_ENABLE_ASSERTIONS={ON,OFF}
LLVM_CCACHE_BUILD={ON,OFF}
-G Ninja
```

May need debug build to debug certain compiler-based issues,
**release + assert** is often used as trade off.

Various resources available online! Start here:

http://llvm.org/docs/GettingStarted.html
https://openmp.llvm.org/SupportAndFAQ.html

# Using LLVM (cheat sheet)

- Use a fast linker (`lld`), `ccache`, and `ninja`
- Consider LTO, either thin or full
- Use tooling (`clang-format`, `clang-tidy`, `clang-modernize`, …)
- Use `-O3/Ofast -march=native` as default
- Online documentation is not great but often not bad either
- Debug with sanitizers enabled
- A release + asserts build is best for every-day use

# Ask the Community

Many ways to interact:

- Discourse (forum/mailing list)
- Discord (persistent chat)
- IRC (non-persistent chat)
- Online Sync-Ups:
  - AA, MLIR, ML, OpenMP, RISC-V, …
- Office Hours ***NEW***
  - “AMA” with an “expert”
- Meetups (soon again!)

# Parallelism in LLVM

# Compiler Optimizations

## Original Program

```
int y = 7;

for (i = 0; i < N; i++) {
  f(y, i);
}
g(y);
```

## After Optimizations

# Compiler Optimizations

## Original Program

```
int y = 7;

for (i = 0; i < N; i++) {
  f(y, i);
}
g(y);
```

## After Optimizations

```
for (i = 0; i < N; i++) {
  f(7, i);
}
g(7);
```

# Compiler Optimizations For Parallel Programs

## Original Program

```
int y = 7;
#pragma omp parallel for
for (i = 0; i < N; i++) {
  f(y, i);
}
g(y);
```

## After Optimizations

# Compiler Optimizations For Parallel Programs?

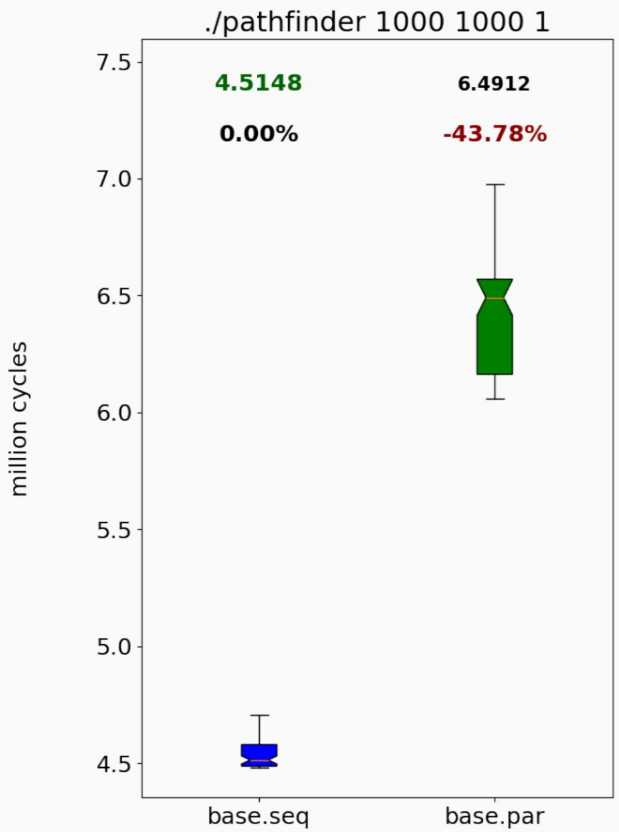
## Original Program

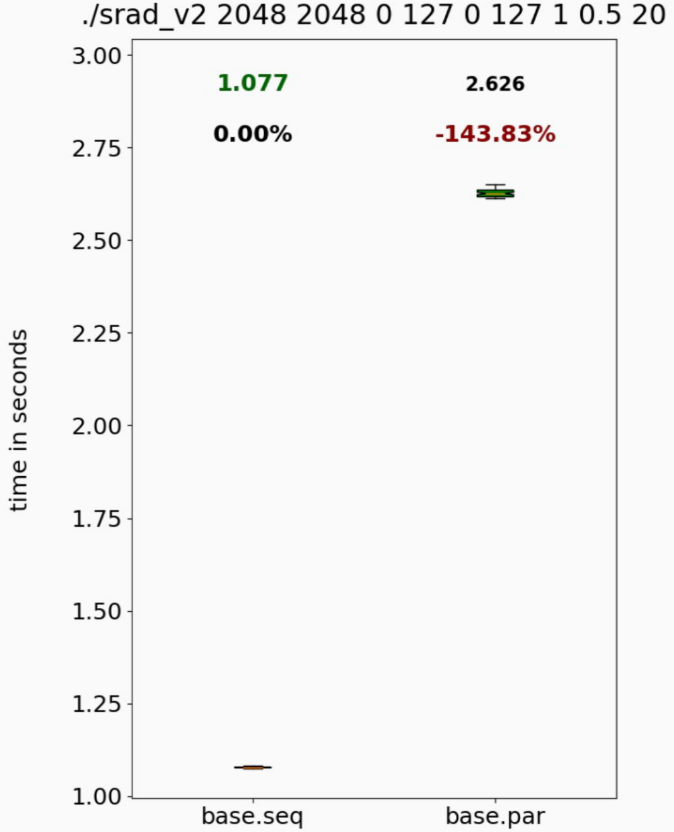
```
int y = 7;
#pragma omp parallel for
for (i = 0; i < N; i++) {
  f(y, i);
}
g(y);
```

## After Optimizations

```
int y = 7;
#pragma omp parallel for
for (i = 0; i < N; i++) {
  f(y, i);
}
g(y);
```

# Compiler Optimizations For Parallel Programs?



# Compiler Optimizations For Parallel Programs?

# LLVM/OpenMP

# OpenMP in LLVM

https://openmp.llvm.org/docs

Slide originally presented at LLVM-Dev Meeting 2020

https://youtu.be/M0DrhQbjrro

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# OpenMP in LLVM

https://openmp.llvm.org/docs

## Clang

OpenMP Parser

OpenMP Sema

OpenMP CodeGen

## OpenMP runtimes

libomp.so (classic, host)

Slide originally presented at LLVM-Dev Meeting 2020

https://youtu.be/M0DrhQbjrro

# OpenMP in LLVM

https://openmp.llvm.org/docs

## Clang

OpenMP Parser

OpenMP Sema

OpenMP CodeGen

## OpenMP runtimes

libomp.so (classic, host)

libomptarget + plugins (offloading, host)

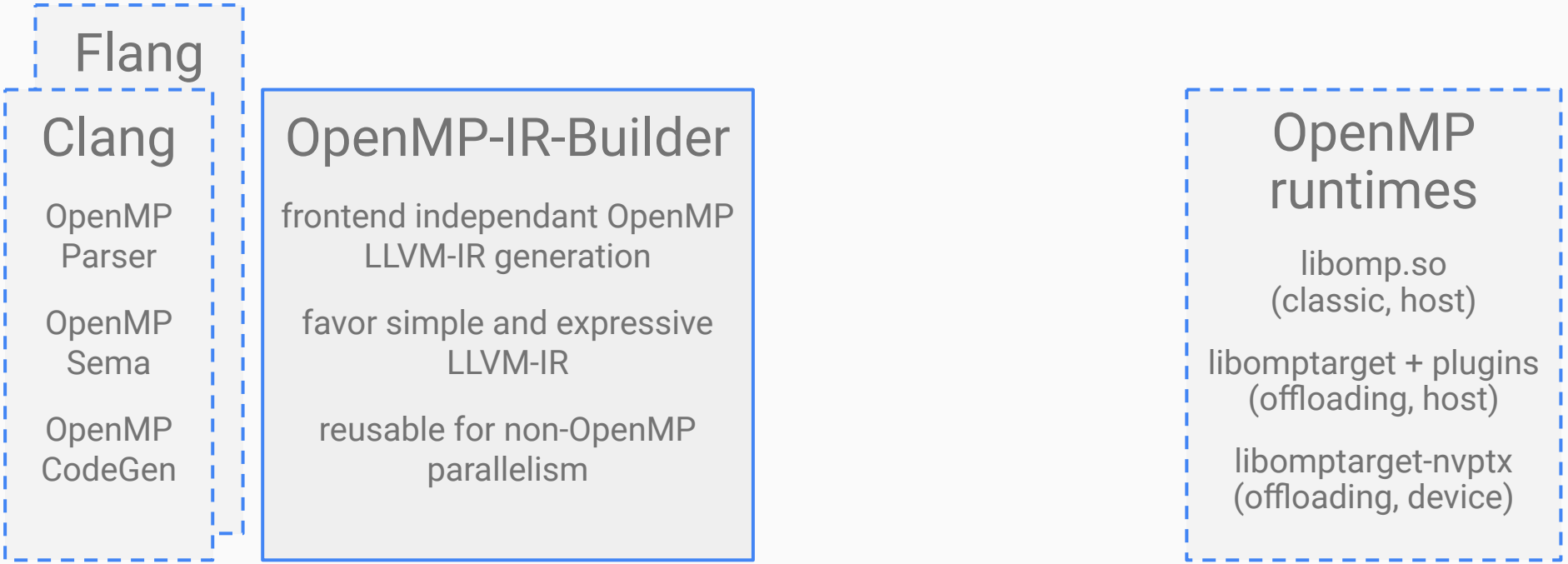
libomptarget-nvptx (offloading, device)

Slide originally presented at LLVM-Dev Meeting 2020

https://youtu.be/M0DrhQbjrro

# OpenMP in LLVM

https://openmp.llvm.org/docs




Slide originally presented at LLVM-Dev Meeting 2020

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# OpenMP in LLVM

https://openmp.llvm.org/docs

Flang

## Clang

OpenMP Parser

OpenMP Sema

OpenMP CodeGen

## OpenMP-IR-Builder

frontend independant OpenMP LLVM-IR generation

favor simple and expressive LLVM-IR

reusable for non-OpenMP parallelism

## OpenMP-Opt

interprocedural optimization pass

contains host & device optimizations

run with -O1 and higher since LLVM 11

## OpenMP runtimes

libomp.so (classic, host)

libomptarget + plugins (offloading, host)

libomptarget-ng-nvptx (offloading, device)

Slide originally presented at LLVM-Dev Meeting 2020

https://youtu.be/M0DrhQbjrro

# LLVM/OpenMP - Learn More

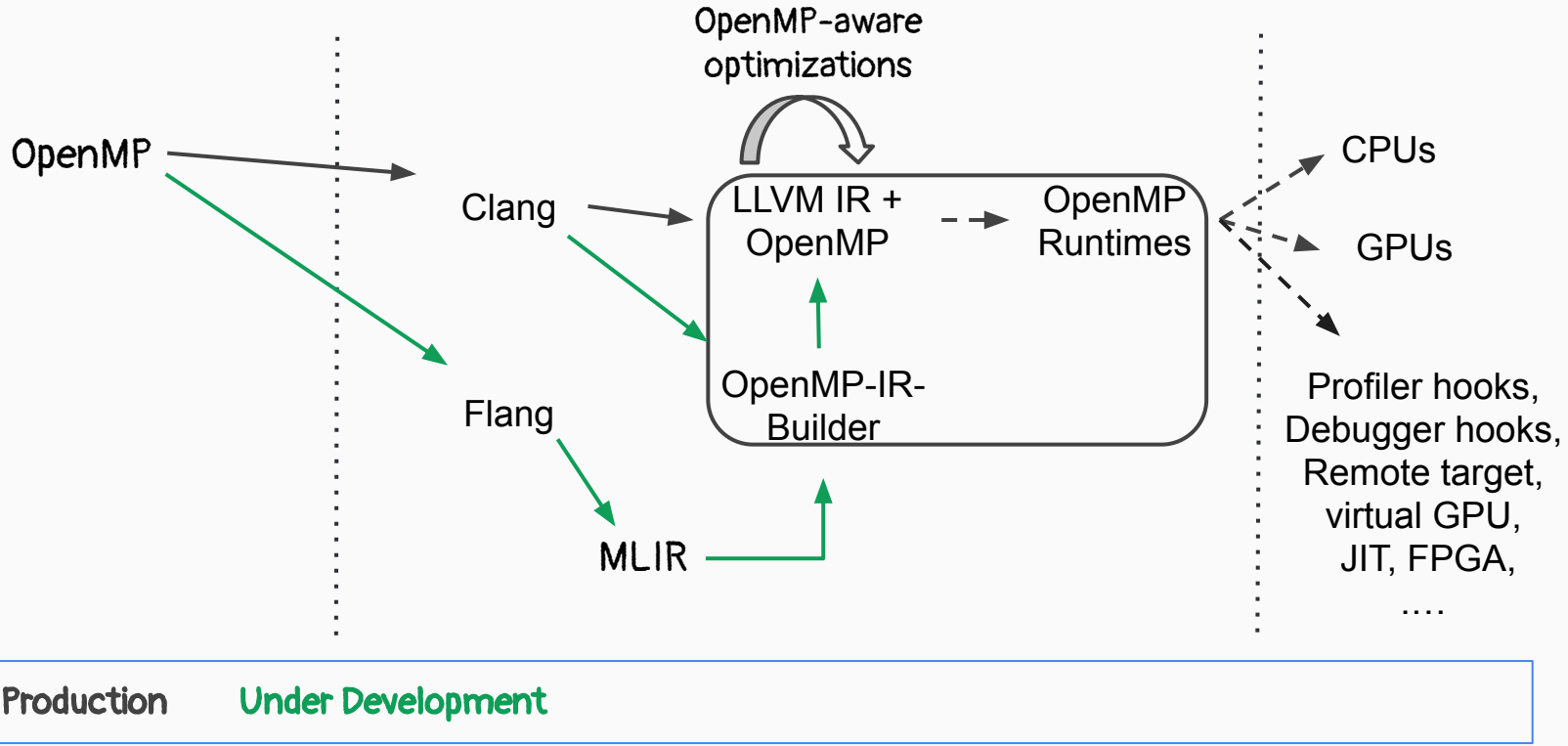
TAKE A PICTURE!

https://youtu.be/R9PUdx1ya1o

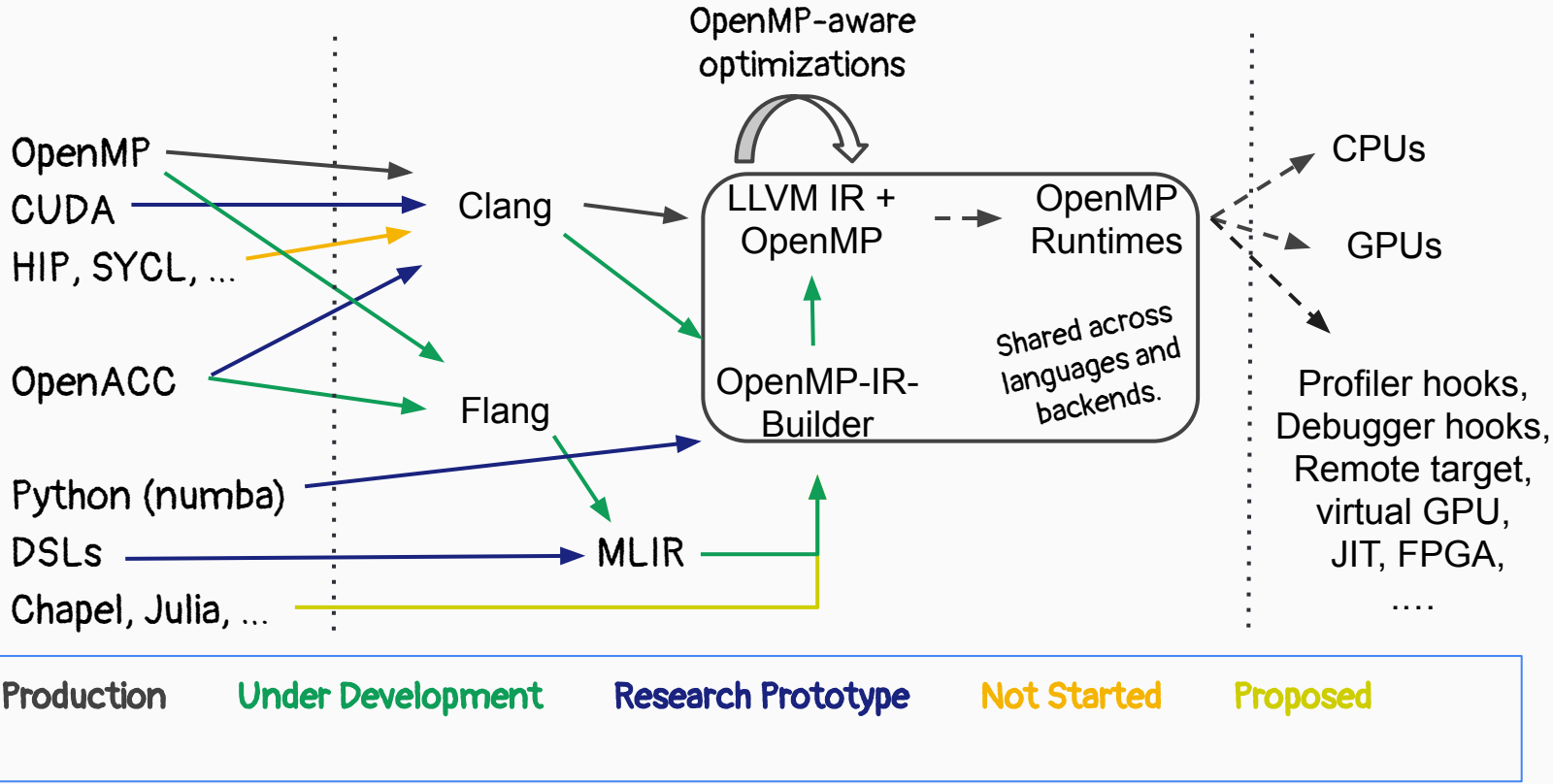
Full 3h tutorial — lots of details

# LLVM/OpenMP – Directions

# Diverse Inputs/Outputs - Uniform Pipeline



# Diverse Inputs/Outputs - Uniform Pipeline



# LLVM/OpenMP – Users and Developers

# Using LLVM/OpenMP Offload (cheat sheet)

- Use a recent (e.g., nightly) compiler version.
- Enable compilation remarks https://openmp.llvm.org/remarks/OptimizationRemarks.html
- Use `LIBOMPTARGET_INFO(=16)` to learn about the GPU execution https://openmp.llvm.org/design/Runtimes.html#libomptarget-info
- Use `LIBOMPTARGET_PROFILE` for built in profiling support.
- Use `LIBOMPTARGET_DEBUG` (and `-fopenmp-target-debug`) for runtime assertions and other opt-in debug features https://openmp.llvm.org/design/Runtimes.html#debugging
- Consider assumptions for better performance:
  `LIBOMPTARGET_MAP_FORCE_ATOMIC=false, -fopenmp-assume-no-thread-state, ...`
- Use device-side LTO `-foffload-lto`

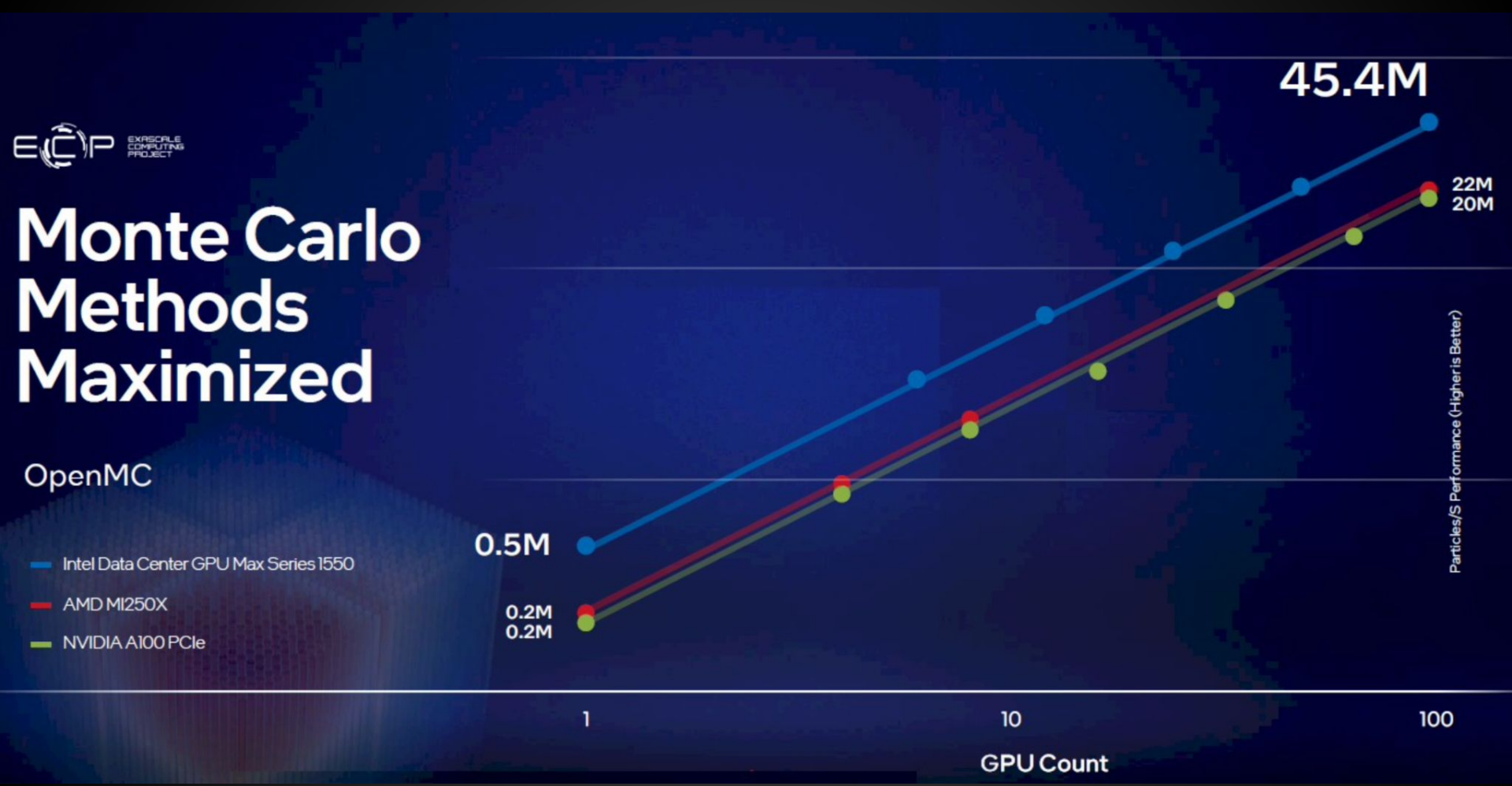
# Getting Involved in LLVM/OpenMP

- LLVM/OpenMP webpage (incl. FAQ)

**Table I: Performance improvements from different optimizations on OpenMC for the HM-large benchmark problem. All optimizations are added to the ones above them in the table.**

| | Optimization Description | Inactive Batch Performance [particles/sec] | Additional Speedup |
|---|---|---|---|
| A | CMake unity build | 602 | - |
| B | -fopenmp-cuda-mode flag usage | 7,714 | 12.8 |
| C | LLVM update() clause optimization | 58,529 | 7.6 |
| D | OpenMC particle object size reduction | 89,732 | 1.5 |
| E | XS lookup kernel optimizations: inlining + reference removal | 117,067 | 1.3 |
| F | Continuous particle refill | 129,345 | 1.1 |
| G | XS lookup queue sort by energy | 164,114 | 1.3 |
| H | Removal of microscopic XS cache | 336,636 | 2.1 |
| I | Increasing number of particles in-flight to 8 million | 349,237 | 1.1 |

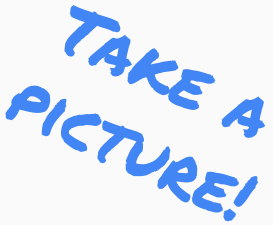
Also, feel free to reach out at any time!




Taken from the Intel Presentation @ ISC'23

# Papers & Presentations
(selection)

Papers:




- Automatic Asynchronous Execution of Synchronously Offloaded OpenMP Target Regions (LLVM-HPC'22)
- Direct GPU Compilation and Execution for Host Applications with OpenMP Parallelism (LLVM-HPC'22)
- Breaking the Vendor Lock --- Performance Portable Programming Through OpenMP as Target Independent Runtime Layer (PACT'22)
- Just-in-Time Compilation and Link Time Optimization for OpenMP Target Offloading (IWOMP'22)
- Efficient Execution of OpenMP on GPUs (CGO'22)
- Co-Designing an OpenMP GPU Runtime Optimizations for Near-Zero Overhead Execution (IPDPS'22)
- Remote OpenMP Offloading (ISC'22, **best paper**)
- Toward Portable GPU Acceleration of the OpenMC Monte Carlo Particle Transport Code (PHYSOR'22)
- A Virtual GPU as Developer-Friendly OpenMP Offload Target (LLPP'21)
- Advancing OpenMP Offload Debugging Capabilities in LLVM (LLPP'21)
- Experience Report: Writing A Portable GPU Runtime with OpenMP 5.1 (IWOMP'21)
- Compiler Optimizations For Parallel Programs (LCPC'18)

Presentations:

A Compiler's View of OpenMP https://www.openmp.org/events/webinar-a-compilers-view-of-the-openmp-api/

# Not OpenMP

# Exploration of AI-enhanced Compilers

## Current Result

- Relative changes(Instruction counts) to baseline, CTMark
  (Trained with test-suite/MultiSource + SingleSource expect for CTMark)

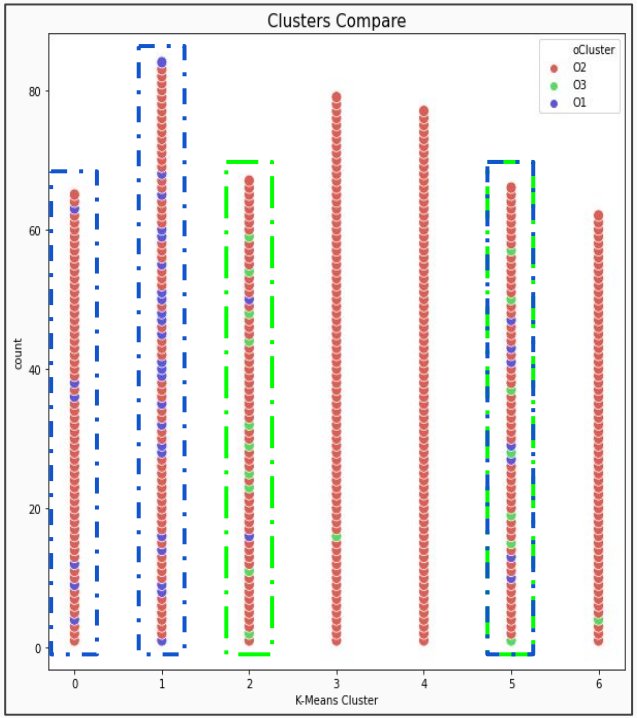
O3

| threshold | compile time | execution time |
|---|---|---|
| prob = 0.5 | -2.74% | +0.1% |
| prob = 0.9 | -4.93% | +0.51% |

aggresive ↓

## AI-based Optimization “skipping”


Hideto Ueno — *University of Tokyo*
Tarindu Jayatilaka — *University of Moratuwa*
Johannes Doerfert — *Lawrence Livermore National Laboratory*
EJ Park — *Los Alamos National Laboratory*
Giorgis Georgakoudis — *Lawrence Livermore National Laboratory*

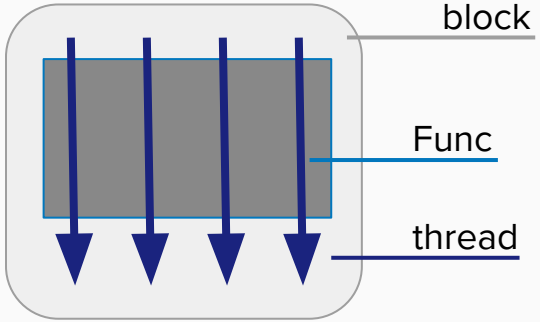

## Code Characterization

# CPU vs GPU Execution Model

# OpenMP Offloading vs Kernel Languages

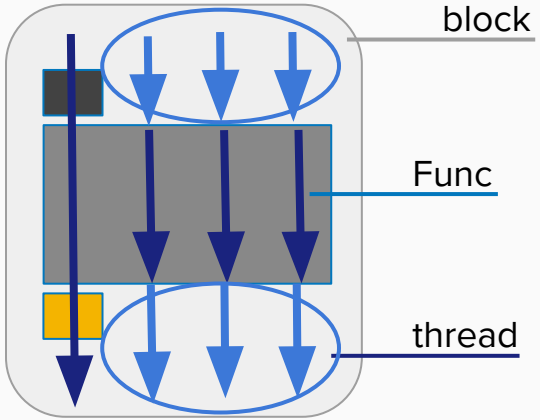
LLVM/OpenMP

```
Func<<</* blocks */ 1, /* threads */ 4>>>(args);
```




SPMD-mode

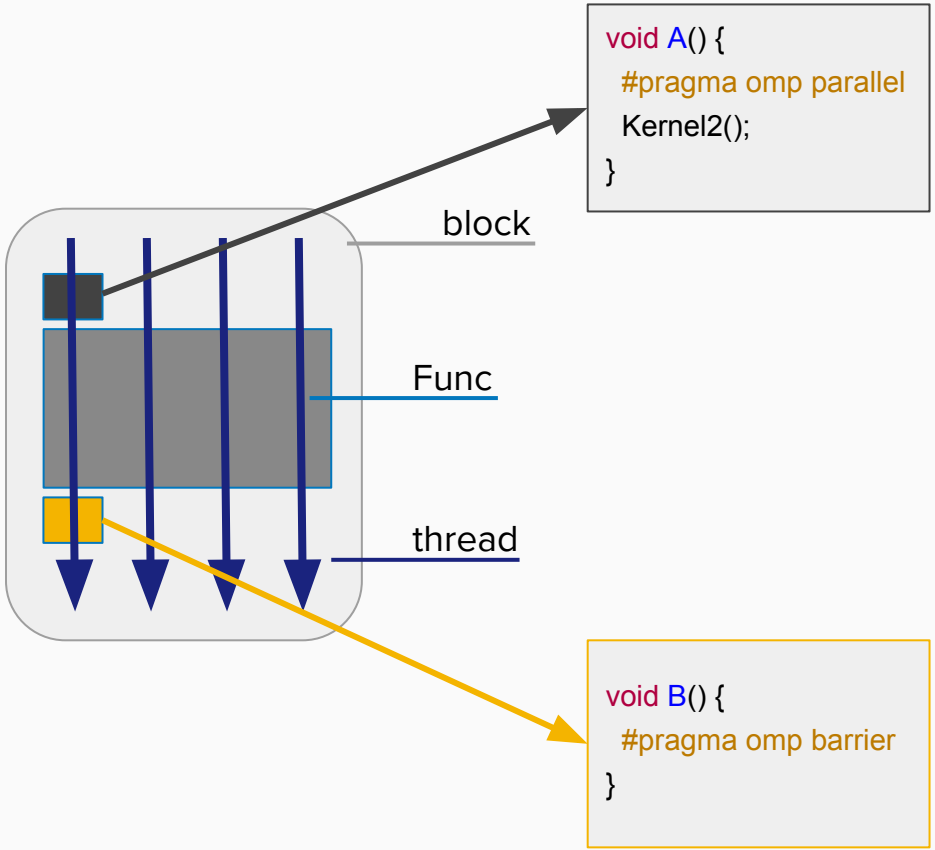
```
#pragma omp target teams num_teams(1)
{
  A();
  #pragma omp parallel num_threads(4) default(firstprivate)
  {
    Func(args);
  }
  B();
}
```




Generic-mode

# OpenMP Offloading vs Kernel Languages

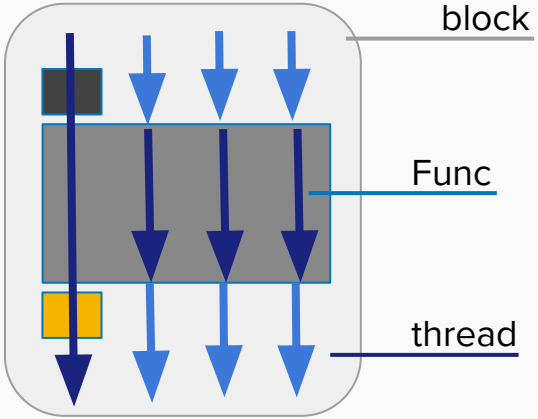
```
#pragma omp target teams num_teams(1)
{
  #pragma omp parallel num_threads(4) default(firstprivate)
  {
    if (omp_get_thread_num() == 0)
      A();
    #pragma omp barrier
    Func(args);
    #pragma omp barrier
    if (omp_get_thread_num() == 0)
      B();
  }
}
```

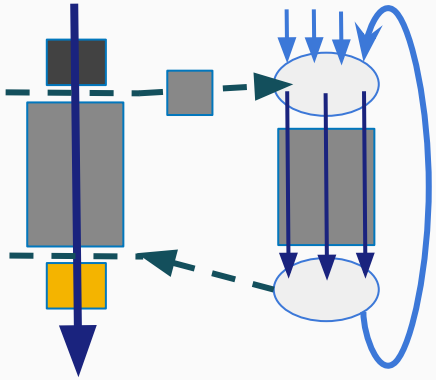



SPMD-zation, since LLVM 14

# OpenMP Offloading vs Kernel Languages (simplified)

```
#pragma omp target teams num_teams(1)
{
  A();
  #pragma omp parallel num_threads(4) default(firstprivate)
  {
    Func(args);
  }
  B();
}
```



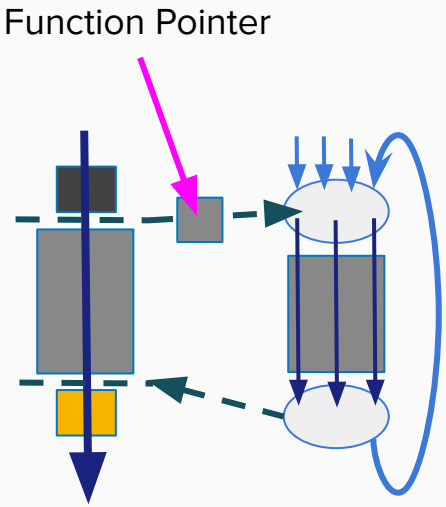
# OpenMP Offloading vs Kernel Languages (simplified)

Q: How do you identify a parallel region?

A: Via the function (pointer) we outlined it into.

Q: Won't that cause indirect calls and spurious call edges?

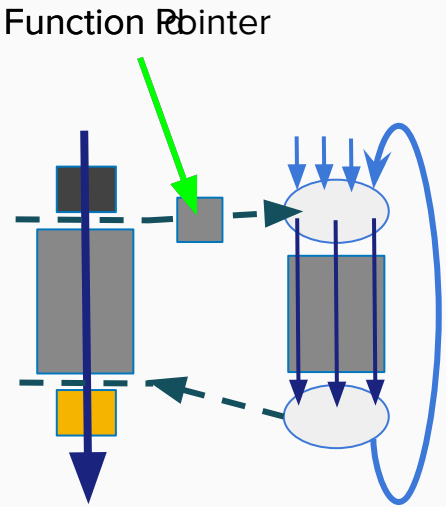
A: Yes. That's why we try to use non-function pointer IDs.



# OpenMP Offloading vs Kernel Languages (simplified)

```
static void parFn() {
  // parallel function code
}

void kernel() {
  if (is_worker()) {
    while (1) {
      fn = __omp_wait_for_parallel();
      fn();
     __omp_inform_parallel_done();
    }
  } else {
    __omp_inform_workers(&parFn, ...)
    parFn();
    __omp_wait_for_workers();
  }
}
```

```
static char parFnId;
static void parFn() {
  // parallel function code
}

void kernel() {
  if (is_worker()) {
    while (1) {
      fn = __omp_wait_for_parallel();
      (fn == &parFnId) ? parFn() : fn();
     __omp_inform_parallel_done();
    }
  } else {
    __omp_inform_workers(&parFnId, ...)
    parFn();
    __omp_wait_for_workers();
  }
}
```



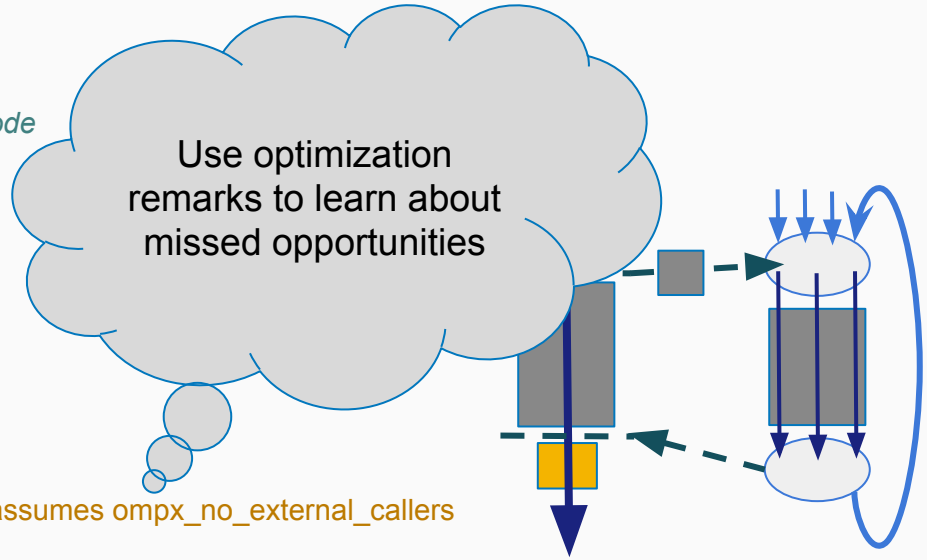

Performed since LLVM 12

# OpenMP Offloading vs Kernel Languages (simplified)

```
static void parFn() {
  // parallel function code
}

void kernel() {
  if (is_worker() {
    // ...
  } else {
    visible();
  }
}


void visible() {
    __omp_inform_workers(&parFn, ...)
    parFn();
    __omp_wait_for_workers();
}
```

```
static char parFnId;
static void parFn() {
  // parallel function code
}

void kernel() {
  if (is_worker() {
    // ...
  } else {
    visible();
  }
}

#pragma omp begin assumes ompx_no_external_callers
void visible() {
    __omp_inform_workers(&parFnId, ...)
    parFn();
    __omp_wait_for_workers();
}
#pragma omp end assumes
```

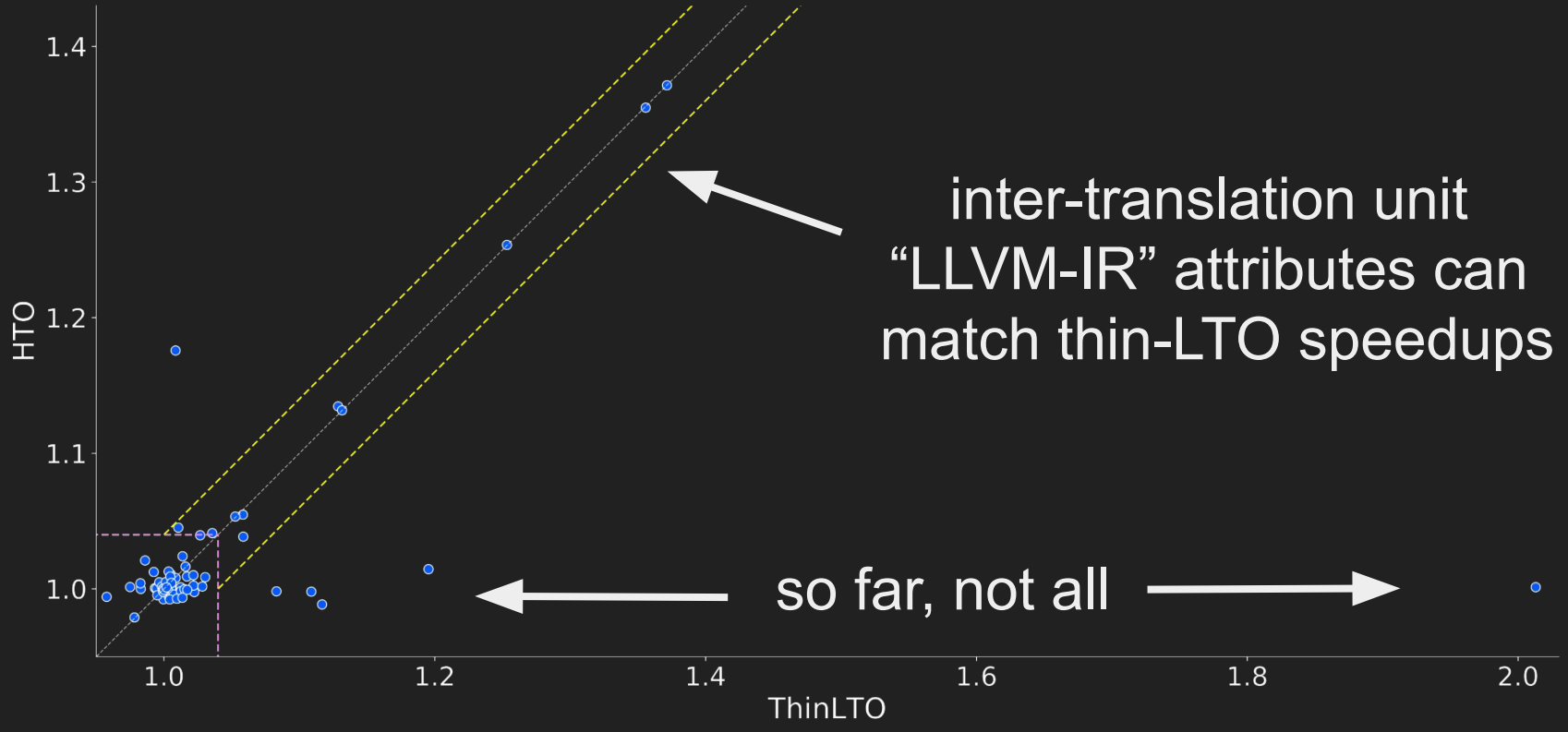
Use optimization remarks to learn about missed opportunities



# Not OpenMP

# The Present and Future of Interprocedural Optimization in LLVM

# Inlining - Alternatives: thin-LTO[7] vs HTO[8]

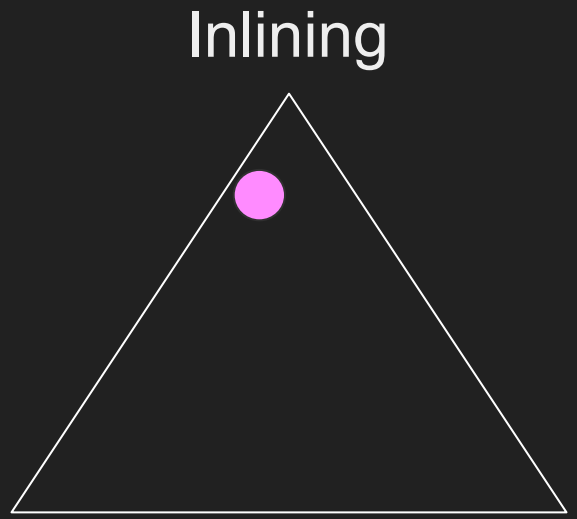



inter-translation unit “LLVM-IR” attributes can match thin-LTO speedups

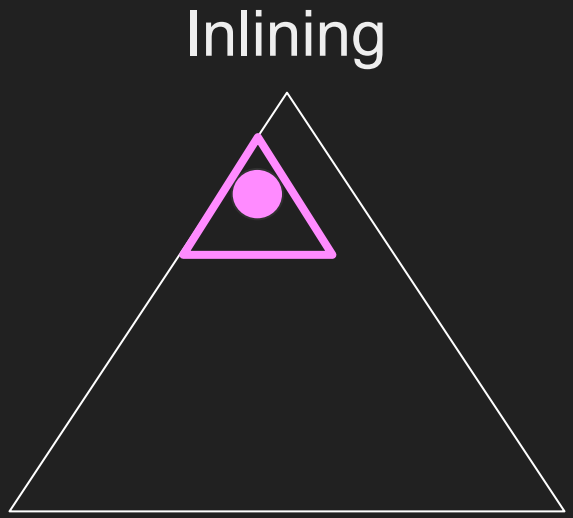
so far, not all

# Design Space

# Design Space



# Design Space




Present Options

Present Default

Interprocedural Optimization

Function Specialization

# Design Space


Present Options

Present Default

Future Default

Interprocedural Optimization

Function Specialization

# Design Space


Present Options

Future Options

Interprocedural Optimization

Present Default

Future Default

Function Specialization

# Design Space


Present Options

Future Options

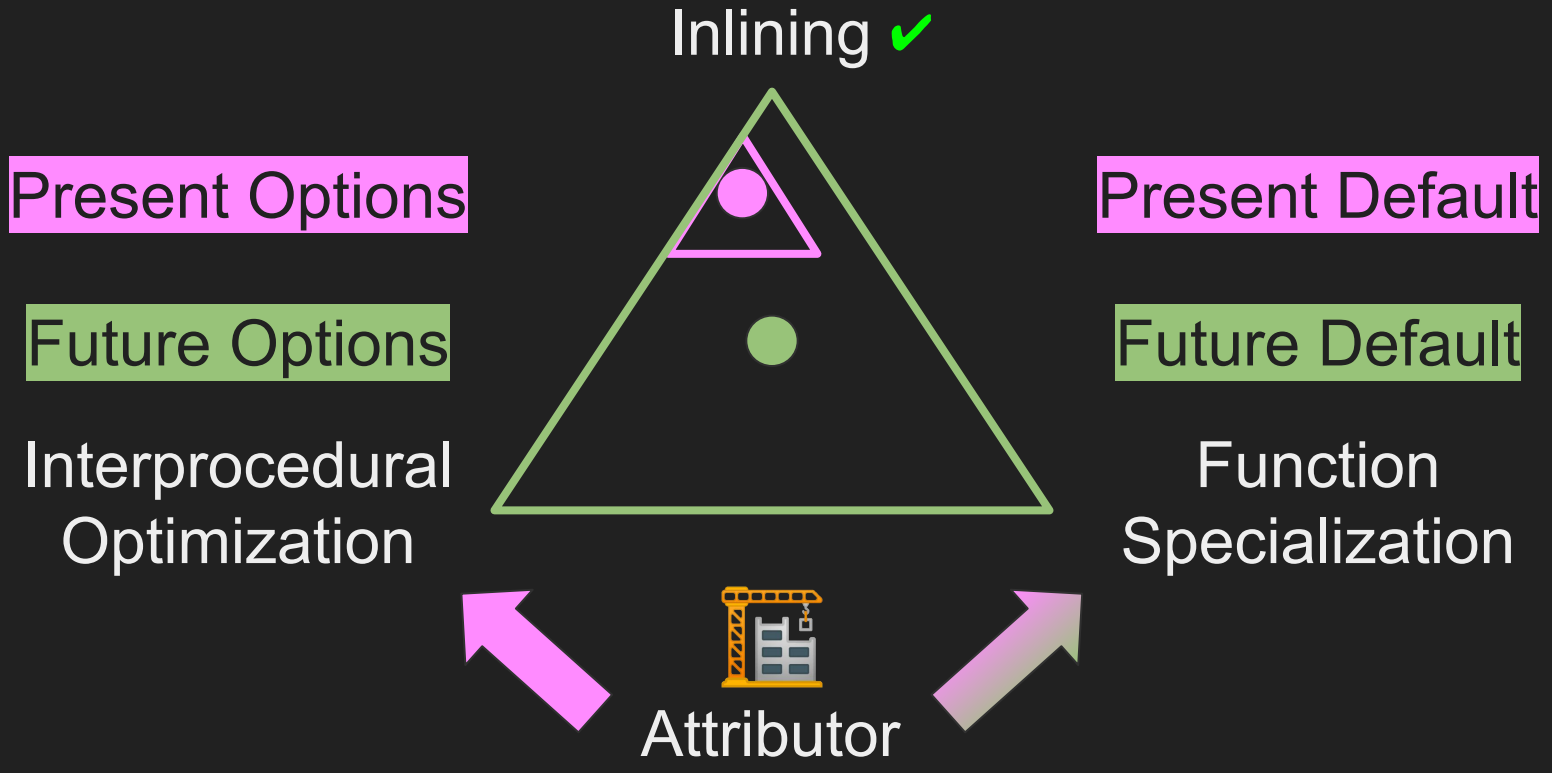
Interprocedural Optimization

Present Default

Future Default

Function Specialization

# Design Space



# Attributor

The Attributor[1,9] is an *interprocedural fixpoint iteration framework*; with lots of built-in features.

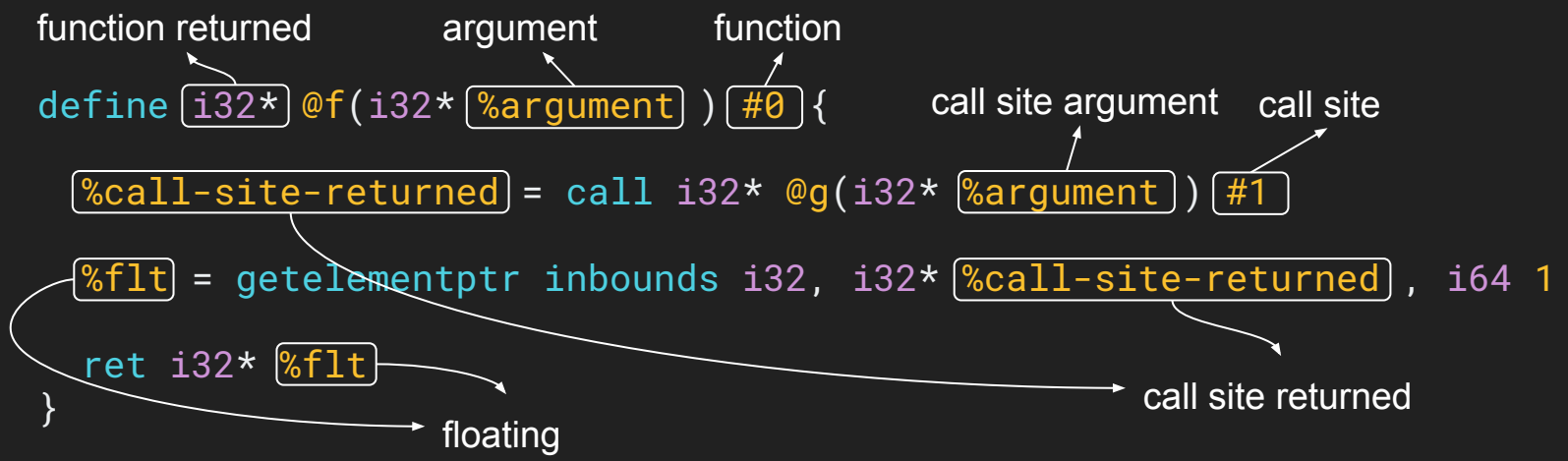
# Phase of Attributor


Determine which kind of deduction or analysis we try to do

Update states till fixpoint is reached

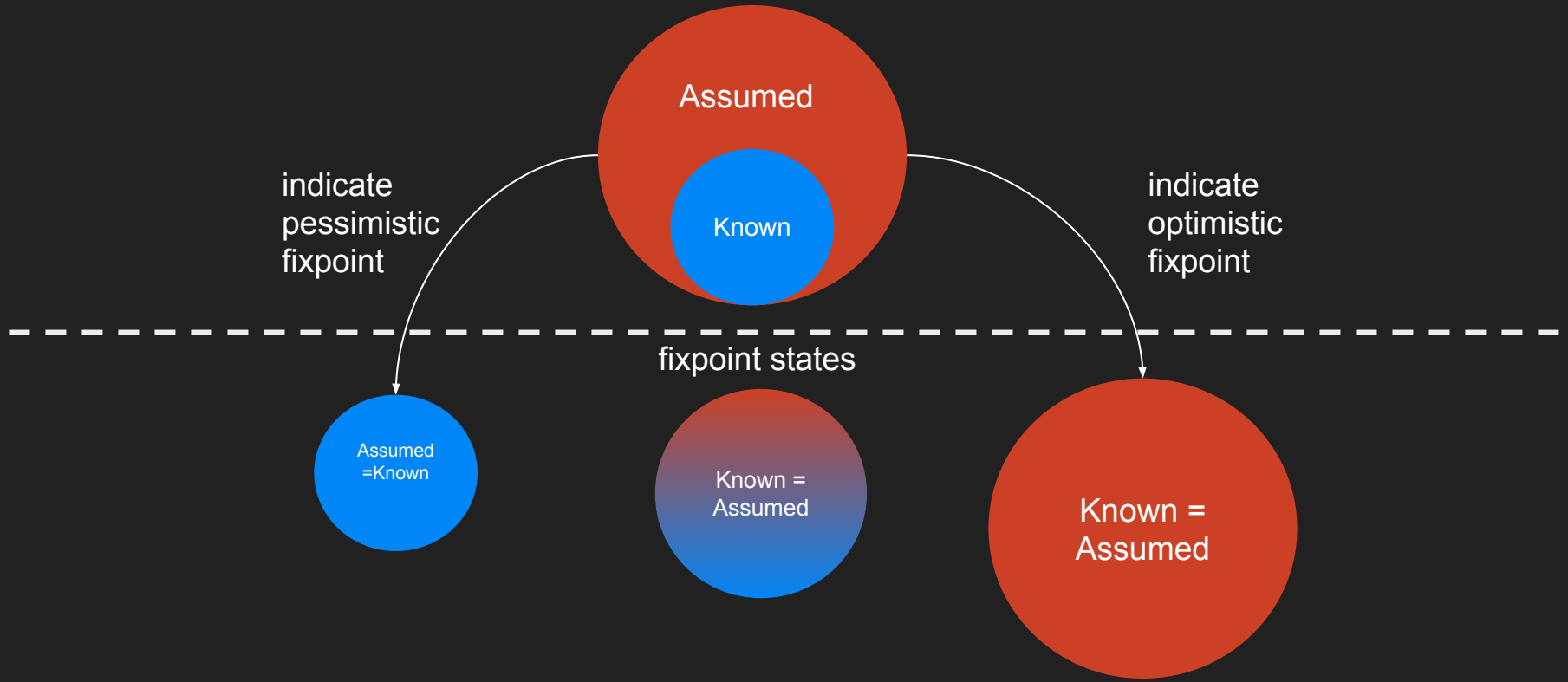
Transform IR according to the results

# LLVM-IR Positions




https://llvm.org/doxygen/structllvm_1_1IRPosition.html

# Abstract state



# The Abstract Attribute (AA) Zoo

AAIsDead
AANoUnwind
AANoSync
AANoRecurse
AAWillReturn
AANoReturn
AAReturnedValues
AANonNull
AANoAlias
AADereferenceable
AAAlign

AANoCapture
AAValueSimplify
AANoFree
AAHeapToStack
AAReachability
AAMemoryBehavior
AAMemoryLocation
AAPrivatizablePtr
AAUndefinedBehavior
AAPotentialValues
AAValueConstantRange

AANoUndef
AACallEdges
AAFunctionReachability
AAPointerInfo
AAAssumptionInfo
AADominance*
AACallGraph*
AAExecutionDomain*
+ AMD GPU Backend
+ OpenMP-Opt

# Attributor Features

- Performance related
  - Dependency types and tracking
  - Dead code “skipping”
  - Selective seeding

- Utility for users
  - Helper classes for generic deduction
  - Helper functions for traversing assumed live uses, basic blocks, call sites, ...
  - Provides a uniform analysis pass query API
  - Time traces, visualization (e.g., dependence graphs)

# Transparent Indirections

The Attributor transparently looks through:

- memory (incl. globals, locals, malloced mem, …)
- calls (incl. indirect* and transitive calls),
- phi-nodes, selects, ...

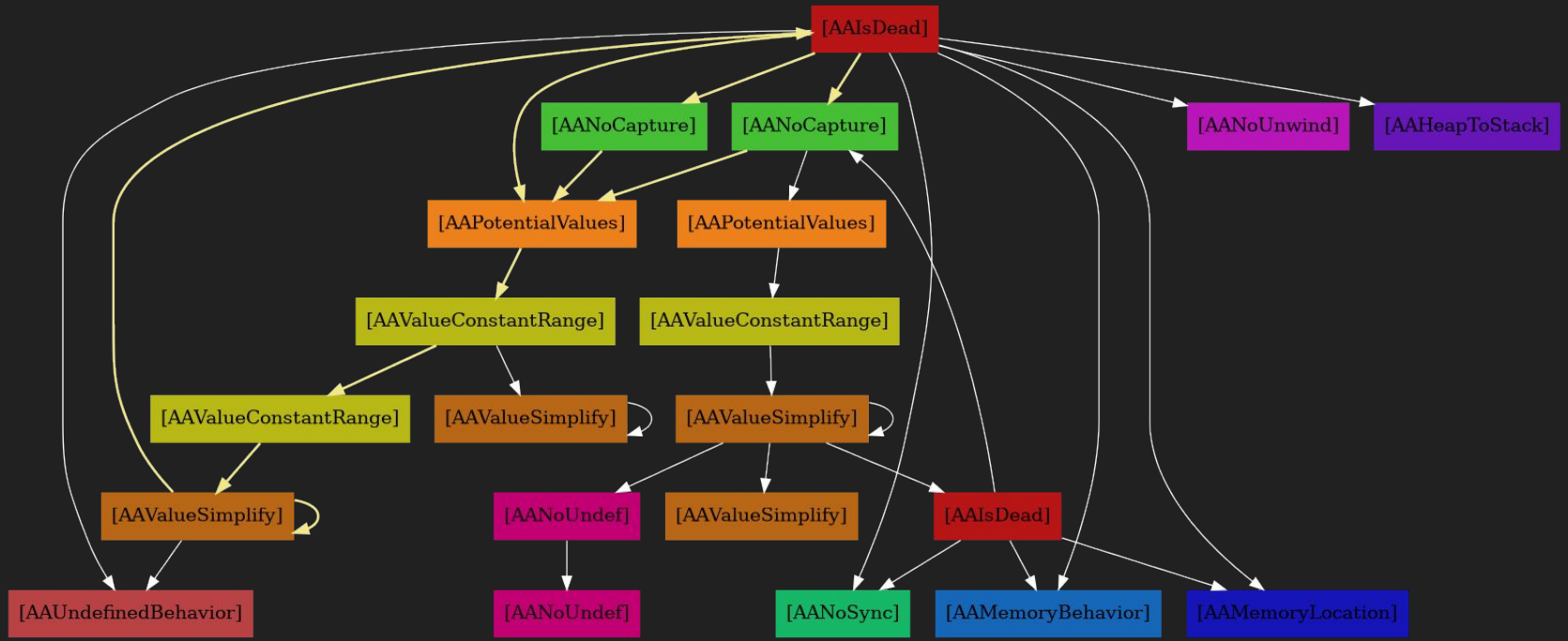
anything “assumed dead” is ignored/hidden by default.

```
struct PTy { int *a; int v; };

void callee(PTy *payload) {
  *payload->a = payload->v;
}

void caller(int * /* align(128) */ A) {
  PTy payload = {A, 42};
  callee(&payload);
}
```

```
struct PTy { int *a; int v; };

void callee(PTy *payload) {
  */* align(128) */payload->a = 42;
}

void caller(int * /* writeonly */ A) {
  PTy payload = {A};
  callee(&payload);
}
```

# Dataflow Iterations

```
void unknown(int &x);
static void check_n_inc(int n, int &x, int &y) {
  if (x) unknown(x);
  if (n) check_n_inc(n-1, y, x);
}

int test(int n) {
  int x = 0, y = 0;
  check_n_inc(n, x, y);
  return x + y;
}
```



# OpenMP → CUDA PTX

# CUDA vs OpenMP Offload

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();


  L = load_data(Buffer, threadIdx.x);
  __syncthreads();


  if (L != 0)
    parallel_work(Buffer, threadIdx.x);


}
```

# CUDA vs OpenMP Offload

```cuda
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```openmp
void openmp() {
  #pragma omp target teams distribute

  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double Buffer[BLOCK_SIZE];

    int L;

    // No conditional, conceptually one thread only
    single_thread_init();
    // No synchronization, again, one thread

    #pragma omp parallel for num_threads(...)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      L = load_data(Buffer, j);
    // Synchronization is implicit

    #pragma omp parallel for num_threads(...)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (L != 0)
        parallel_work(Buffer, j);


  }
}
```

# CUDA vs OpenMP Offload — Globalization of Locals

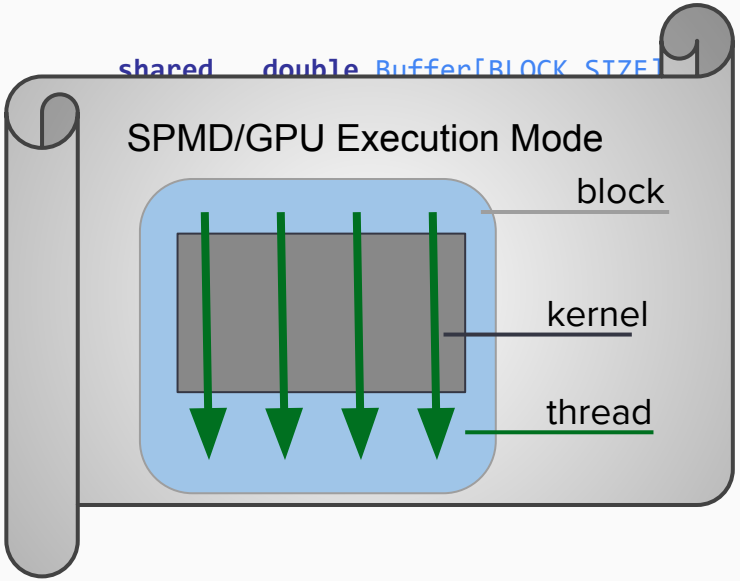
```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init()
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```
void openmp_impl() {
  #pragma omp target teams distribute

  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double *Buffer = __omp_alloc(8 * BLOCK_SIZE);

    int *L = __omp_alloc(sizeof(int));

    // No conditional, conceptually one thread only
    single_thread_init();
                                        one thread

                                    threads(...) shared(L)
                                    E; ++j)

    // Synchronization is implicit

    #pragma omp parallel for num_threads(...) shared(L)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (*L != 0)
        parallel_work(Buffer, j);

    __omp_free(...)
  }
}
```

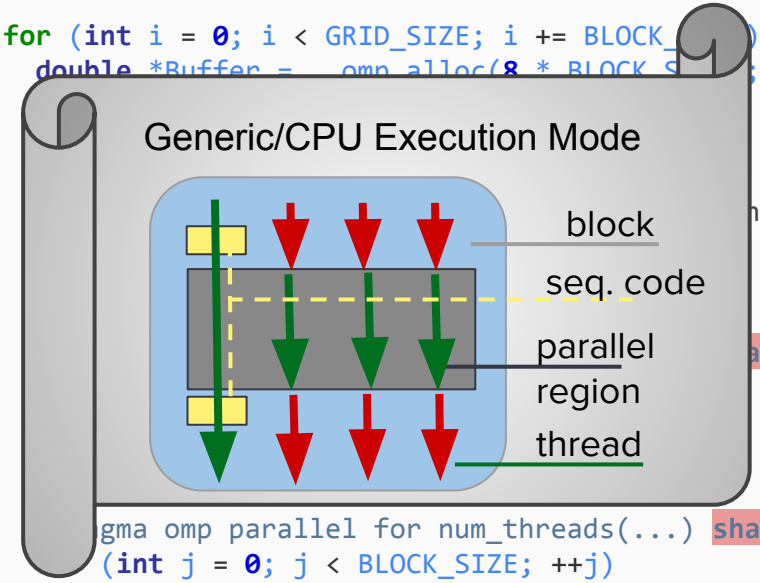
Local/Stack variables cannot be shared across GPU threads.

# CUDA vs OpenMP Offload — Execution Mode Mismatch

```
__global__ void cuda() {
  __shared__ double Buffer[BLOCK_SIZE];

  if (L != 0)
    parallel_work(Buffer, threadIdx.x);

}
```




```
void openmp_impl() {
  #pragma omp target teams distribute
  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double *Buffer = __omp_alloc(8 * BLOCK_SIZE);

    #pragma omp parallel for num_threads(...) shared(L)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (*L != 0)
        parallel_work(Buffer, j);

    __omp_free(...)
  }
}
```



# CUDA vs OpenMP Offload — Globalization of Locals

```cuda
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```openmp
void openmp_impl() {
  #pragma omp target teams distribute

  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double *Buffer = __omp_alloc(8 * BLOCK_SIZE);

    int *L = __omp_alloc(sizeof(int));

    // No conditional, conceptually one thread only
    single_thread_init();
    // No synchronization, again, one thread

    #pragma omp parallel for num_threads(...) shared(L)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      *L = load_data(Buffer, j);
    // Synchronization is implicit

    #pragma omp parallel for num_threads(...) shared(L)
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (*L != 0)
        parallel_work(Buffer, j);

    __omp_free(...)
  }
}
```

# OpenMP-Opt — Deglobalization

See: CGO'22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```
void openmp_impl() {
  #pragma omp target teams distribute

  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer) allocator(cgroup)
    int L;
    #pragma omp allocate(L) allocator(thread)
    // No conditional, conceptually one thread only
    single_thread_init();
    // No synchronization, again, one thread

    #pragma omp parallel for
    for (int j = 0; j < BLOCK_SIZE; ++j)
      L = load_data(Buffer, j);
    // Synchronization is implicit

    #pragma omp parallel for
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (L != 0)
        parallel_work(Buffer, j);


  }
}
```

# OpenMP-Opt — “SPMDzation”

See: CGO’22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();


  L = load_data(Buffer, threadIdx.x);
  __syncthreads();


  if (L != 0)
    parallel_work(Buffer, threadIdx.x);


}
```

```
void openmp_impl() {
  #pragma omp target teams distribute
  #pragma omp parallel
  for (int i = 0; i < GRID_SIZE; i += BLOCK_SIZE) {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer) allocator(cgroup)
    int L;
    #pragma omp allocate(L) allocator(thread)
    if (__omp_get_thread_id() == 0)
      single_thread_init();
    #pragma omp barrier // aligned

    #pragma omp for nowait
    for (int j = 0; j < BLOCK_SIZE; ++j)
      L = load_data(Buffer, j);
    #pragma omp barrier // aligned

    #pragma omp for nowait
    for (int j = 0; j < BLOCK_SIZE; ++j)
      if (L != 0)
        parallel_work(Buffer, j);
    #pragma omp barrier // aligned

  }
}
```

# OpenMP-Opt — Loop Oversubscription (User Assumption)

See: CGO'22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();


  L = load_data(Buffer, threadIdx.x);
  __syncthreads();


  if (L != 0)
    parallel_work(Buffer, threadIdx.x);


}
```

```
void openmp_impl() {
  #pragma omp target teams parallel
  int i = omp_get_team_num();
  if (i < GRID_SIZE) {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer) allocator(cgroup)
    int L;
    #pragma omp allocate(L) allocator(thread)
    if (__omp_get_thread_id() == 0)
      single_thread_init();
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      L = load_data(Buffer, j);
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      if (L != 0)
        parallel_work(Buffer, j);
    #pragma omp barrier // aligned

  }
}
```

# OpenMP-Opt — Aligned Barrier Removal

See: CGO'22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```
void openmp_impl() {
  #pragma omp target teams parallel
  int i = omp_get_team_num();
  if (i < GRID_SIZE) {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer) allocator(cgroup)
    int L;
    #pragma omp allocate(L) allocator(thread)
    if (__omp_get_thread_id() == 0)
      single_thread_init();
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      L = load_data(Buffer, j);
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      if (L != 0)
        parallel_work(Buffer, j);
    #pragma omp barrier // aligned

  }
}
```

# OpenMP-Opt — Runtime Call Specialization

See: CGO'22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();


  L = load_data(Buffer, threadIdx.x);
  __syncthreads();


  if (L != 0)
    parallel_work(Buffer, threadIdx.x);


}
```

```
void openmp_impl() {
  #pragma omp target teams parallel
  int i = omp_get_team_num();
  if (i < GRID_SIZE) {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer
    int L;
    #pragma omp allocate(L) allocator(thread)
    if (__omp_get_thread_id() == 0)
      single_thread_init();
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      L = load_data(Buffer, j);
    #pragma omp barrier // aligned

    int j = omp_get_thread_num();
    if (j < BLOCK_SIZE)
      if (L != 0)
        parallel_work(Buffer, j);


  }
}
```

num_teams(GRID_SIZE)
thread_limit(BLOCK_SIZE)

# OpenMP-Opt — CUDA-like Kernel Code

See: CGO'22

```
__global__ void cuda() {


  __shared__ double Buffer[BLOCK_SIZE];

  int L;

  if (threadIdx.x == 0)
    single_thread_init();
  __syncthreads();



  L = load_data(Buffer, threadIdx.x);
  __syncthreads();



  if (L != 0)
    parallel_work(Buffer, threadIdx.x);



}
```

```
void openmp_impl() {
  #pragma omp target teams parallel

  {
    double Buffer[BLOCK_SIZE];
    #pragma omp allocate(Buffer) allocator(cgroup)
    int L;
    #pragma omp allocate(L) allocator(thread)
    if (__omp_get_thread_id() == 0)
      single_thread_init();
    #pragma omp barrier // aligned



    L = load_data(Buffer, j);
    #pragma omp barrier // aligned

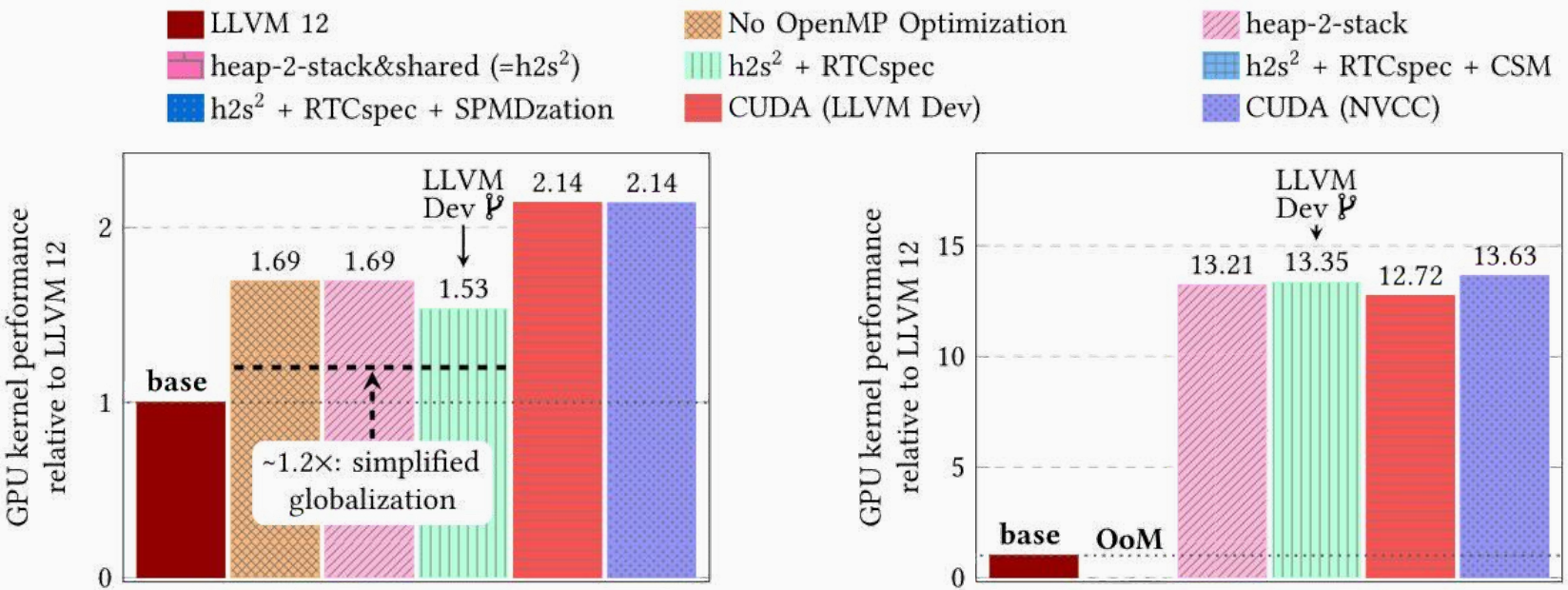


    if (L != 0)
      parallel_work(Buffer, j);


  }
}
```

# Optimized OpenMP Offload Performance

See: CGO'22

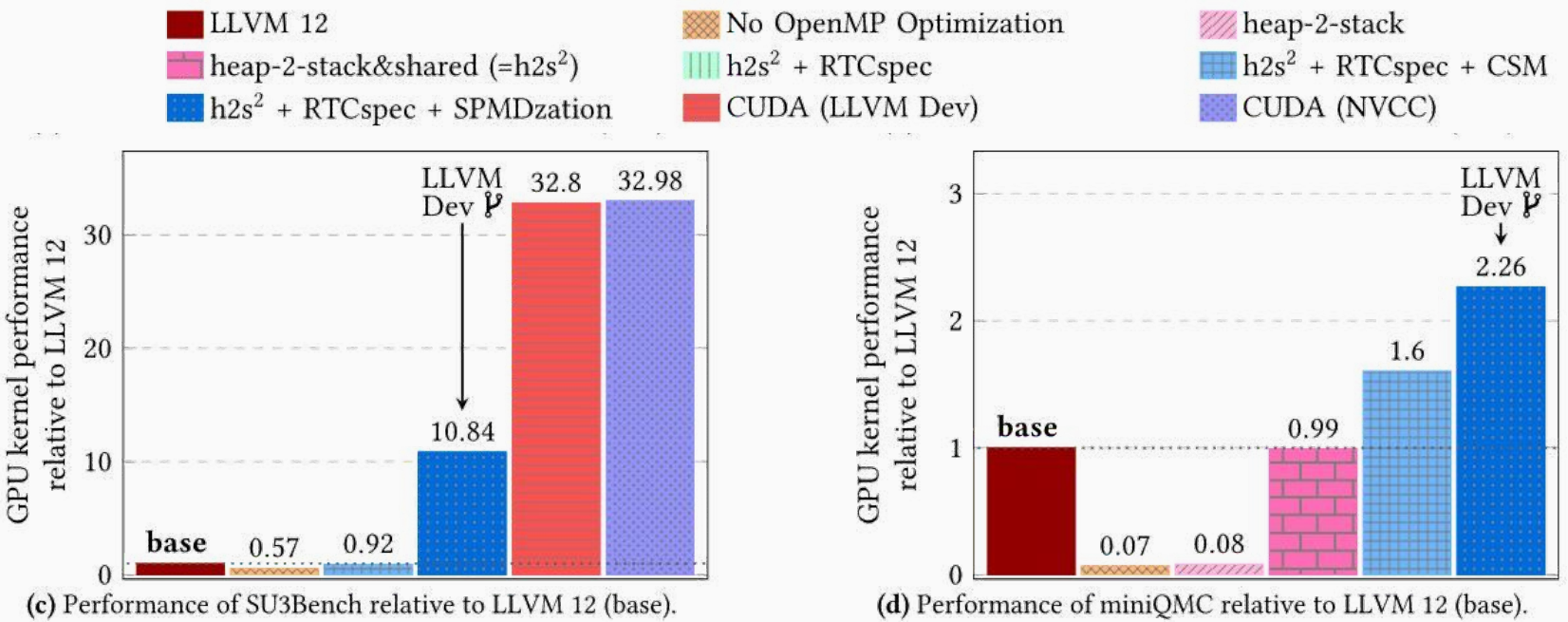



(a) Performance of XSBench relative to LLVM 12 (base).

(b) Performance of RSBench relative to LLVM 12 (base).

# Optimized OpenMP Offload Performance

See: CGO'22




**(c)** Performance of SU3Bench relative to LLVM 12 (base).

**(d)** Performance of miniQMC relative to LLVM 12 (base).

# Co-Designing Opt. & Portable GPU Runtime

# Explicit (Shared) Global State and Powerful IPO

```
__shared__ StateTy State;

__global__ void kernel() {
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}
```

```
__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(State.TeamSize);
}
```

# Explicit (Shared) Global State and Powerful IPO

```
__shared__ StateTy State;

__global__ void kernel() {
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {
  if (State.TeamSize > 1)
    return __omp_parallel_sequentialized(fn, ...);
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = blockDim.x;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  fn();
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(State.TeamSize);
}
```

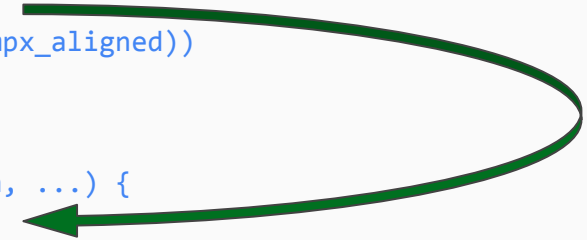
# Explicit (Shared) Global State and Powerful IPO

```
__shared__ StateTy State;

__global__ void kernel() {
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {
  if (1 > 1)
    return __omp_parallel_sequentialized(fn, ...);
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = blockDim.x;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  fn();
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(State.TeamSize);
}
```



IP-Reachability +
shared memory lifetime

# Explicit (Shared) Global State and Powerful IPO

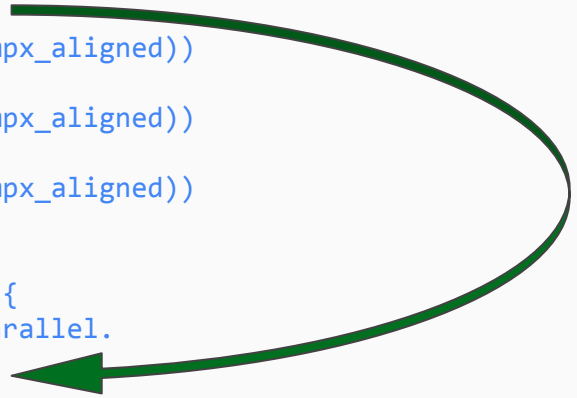
```
__shared__ StateTy State;

__global__ void kernel() {
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {


  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = blockDim.x;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  fn();
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(blockDim.x);
}
```



IP-Reachability + shared memory lifetime + IP-Dominance + intrinsic annotations

# Explicit (Shared) Global State and Powerful IPO

```
__shared__ StateTy State;

__global__ void kernel() {
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {


  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = blockDim.x;
  __omp_aligned_barrier(); // assume((ompx_aligned))
  fn();
  __omp_aligned_barrier(); // assume((ompx_aligned))
  State.TeamSize = 1;
  __omp_aligned_barrier(); // assume((ompx_aligned))
}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(blockDim.x);
}
```

shared memory lifetime + IP-write-only

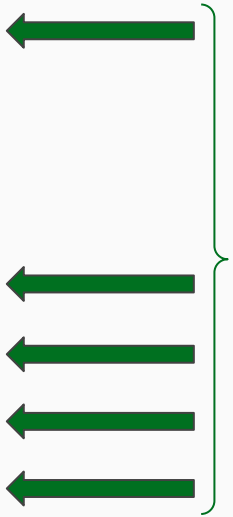
shared memory lifetime + IP-DSE

# Explicit (Shared) Global State and Powerful IPO

```
__global__ void kernel() {
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_aligned_barrier(); // assume((ompx_aligned))
  fn();
  __omp_aligned_barrier(); // assume((ompx_aligned))
  __omp_aligned_barrier(); // assume((ompx_aligned))
}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(blockDim.x);
}
```



IP-aligned barrier elimination

# Explicit (Shared) Global State and Powerful IPO

```
__global__ void kernel() {

  __omp_parallel(outlined_fn, ...);
}

__device__ static void __omp_parallel(fn, ...) {

  fn();

}

__device__ static void outlined_fn(...) {
  // Do not (transitively) call __omp_parallel.
  use(blockDim.x);
}
```

```
__global__ void kernel() {
  use(blockDim.x);
}
```

Simplifications, e.g., inlining, remove (now empty) abstraction layers.

⇒ CUDA-like code (IR and PTX)

# Remarks & Assumptions - Interactive Optimization

OpenMP-Opt emits remarks:

- -Rpass=openmp-opt
- -Rpass-missed=openmp-opt
- -Rpass-analysis=openmp-opt

to report success and failure,

and utilizes assumptions:

- `#pragma omp assumes ...`
- `__attribute__((assume("...")))`
- command line flags

to enhance static analysis.

*New* environment assumptions:
`LIBOMPTARGET_MAP_FORCE_ATOMIC=false`

OpenMP 5.1 spec assumptions:

```
omp_no_openmp
omp_no_parallelism
omp_no_openmp_routines
```

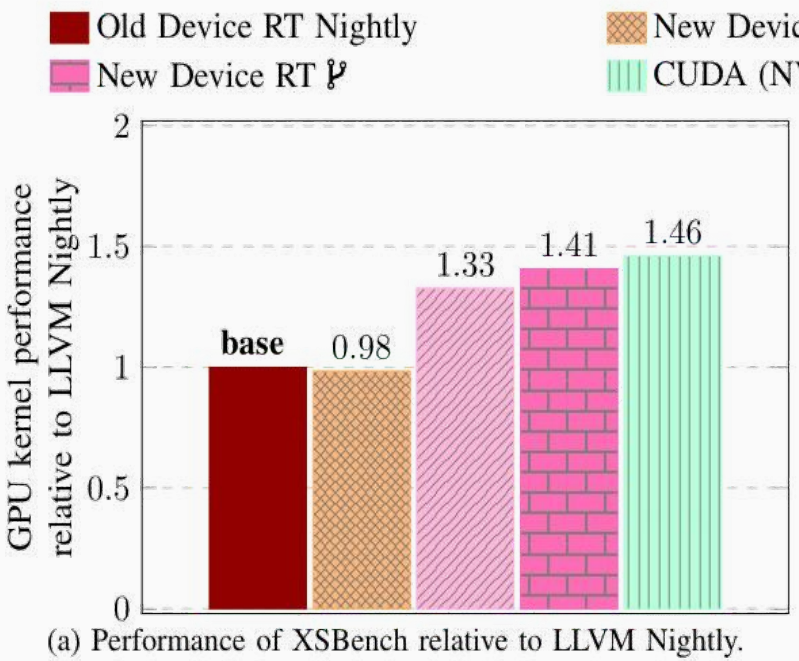
LLVM assumption extensions:

```
ompx_spmd_amenable
ompx_aligned_barrier
ompx_no_sync
```

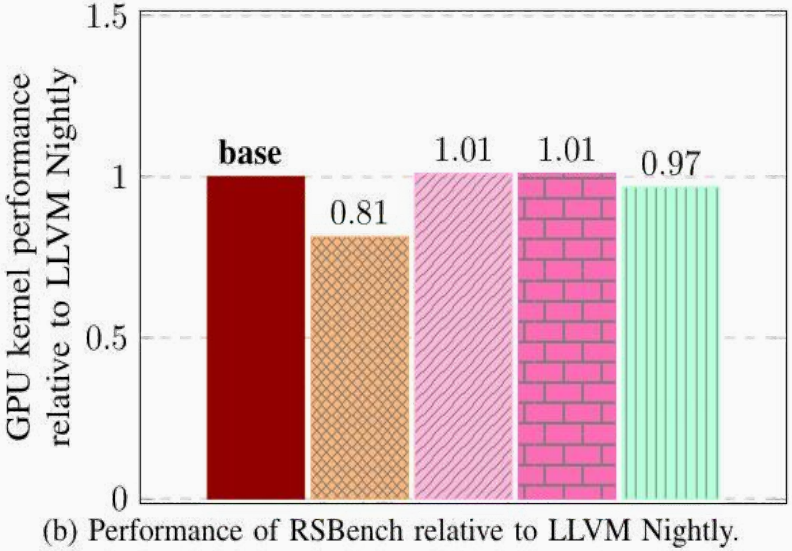
```
-fopenmp-cuda-mode
-fopenmp-assume-no-nested-parallelism
-fopenmp-assume-no-thread-state
-fopenmp-assume-teams-oversubscription
-fopenmp-assume-threads-oversubscription
```

# Optimized OpenMP Offload Performance

See: IPDPS'22



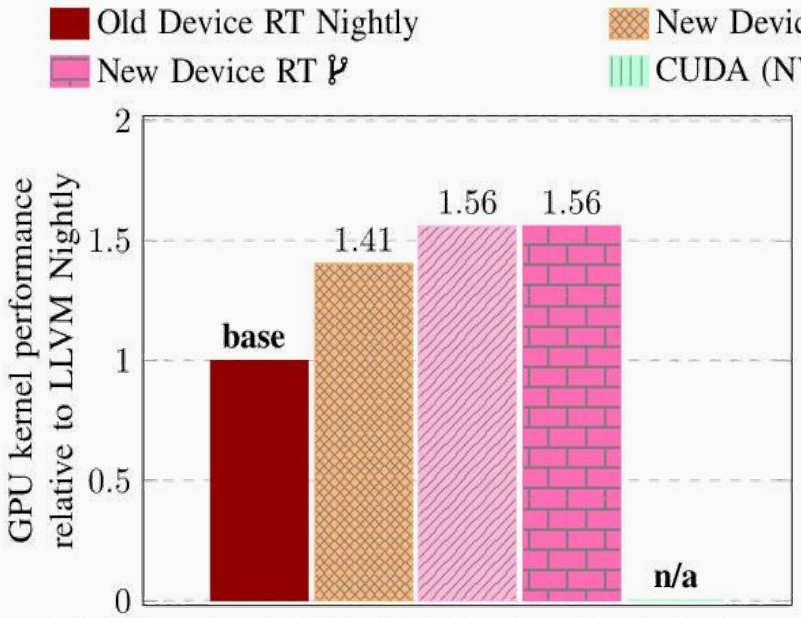

(a) Performance of XSBench relative to LLVM Nightly.



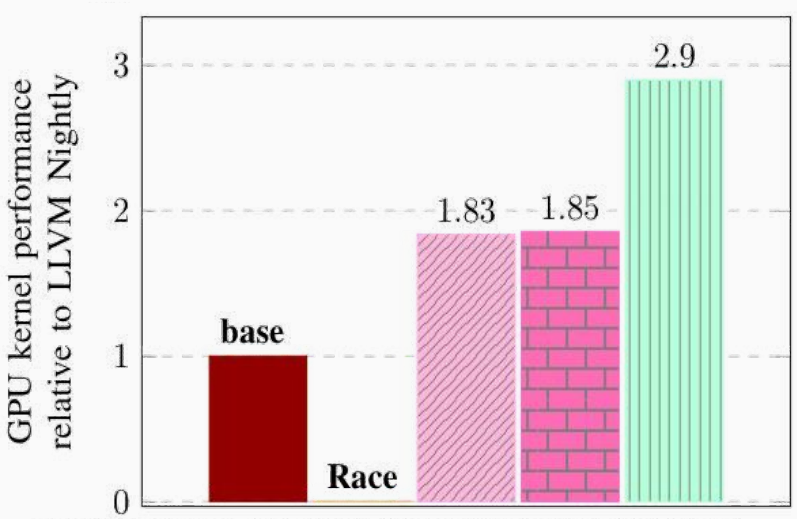

(b) Performance of RSBench relative to LLVM Nightly.

# Optimized OpenMP Offload Performance

See: IPDPS'22




(c) Performance of TestSNAP relative to LLVM Nightly.




(d) Performance of MiniFMM relative to LLVM Nightly.

# Cuda-like OpenMP

# Offload Style

```
int i = blockId.x;
if (i >= N) return;
int j = threadId.x;
if (j >= M) return;
body1(i, j);
__syncthreads();
body2(i, j);
}
```

# Offload Style

```
int i = blockId.x;
if (i >= N) return;
int j = threadId.x;
if (j >= M) return;
body1(i, j);
__syncthreads();
body2(i, j);
}
```

```
#pragma omp target teams distribute
for (int i = ...) {
  #pragma omp parallel for
  for (int j = ...)
    body1(i, j);
  #pragma omp parallel for
  for (int j = ...)
    body2(i, j);
}
```

# Offload Style

```
int i = blockId.x;
if (i >= N) return;
int j = threadId.x;
if (j >= M) return;
body1(i, j);
__syncthreads();
body2(i, j);
}
```

```
#pragma omp target loop
for (int i = ...) {
  #pragma omp loop
  for (int j = ...)
    body1(i, j);
  #pragma omp loop
  for (int j = ...)
    body2(i, j);
}
```

# OpenMP Kernel Language

# libompx — Host Wrappers

```
_LIBOMPX_NAMESPACE_BEGIN

extern "C" void *ompx_malloc(size_t size) {
  if (size <= 0)
    return nullptr;
  return omp_target_alloc(size, omp_get_default_device());
}

void *ompx::malloc(size_t size) { return ompx_malloc(size); }

_LIBOMPX_NAMESPACE_END
```

# libompx — Device Wrappers

```
/// AMDGCN Implementation
///
///{
#pragma omp begin declare variant match(device = {arch(amdgcn)})

uint32_t ompx_get_thread_num(int Dim = 0) {
  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();
    default:break;
  }
  __builtin_unreachable();
}

...

#pragma omp end declare variant
```

# [1/2] CUDA Syntax

```
kern<<<nblocks, nthreads, shmem>>>(a1, a2)
```

```
#pragma omp target teams num_teams(nblocks) thread_limit(nthreads) \
                         ompx_cgroup_dyn_mem(shmem) ompx_kernel
kern(a1, a2)
```

# [2/2] CUDA Syntax

```
__device__ void foo();
```

```
void foo();
#pragma omp declare target device_type(nohost) to(foo)
```

# [2/2] CUDA Syntax

```
__device__ void foo();
```

```
[[ompx::declare_target(device_type(nohost))]] void foo();
```

# Not OpenMP

# Performance Exploration Through Optimistic Static Program Annotations

Johannes Doerfert
Argonne National Laboratory

Brian Homerding
Argonne National Laboratory

Hal Finkel
Argonne National Laboratory

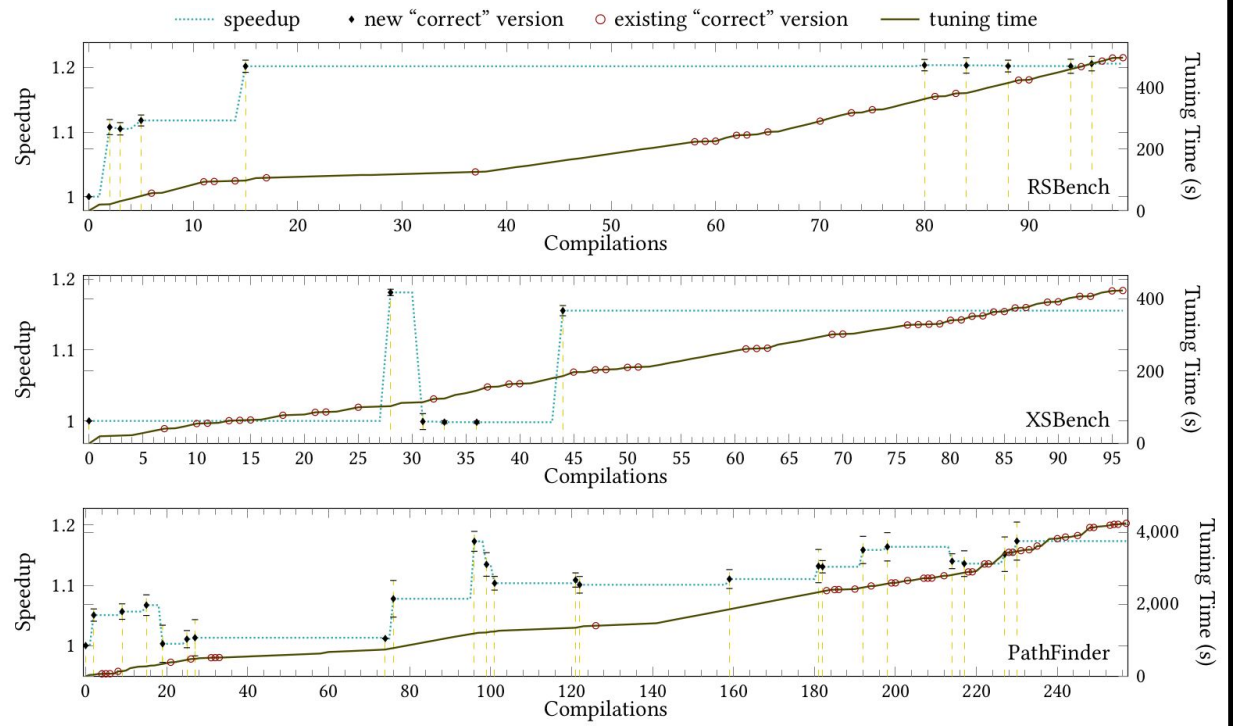



**Table 3.** Optimistic optimization opportunities exploited and the sections in which they are discussed.

| | |
|---|---|
| potentially overflowing computations | Section 3.1 |
| potentially parallel loops | Section 3.2 |
| unknown control flow choices | Section 3.3 |
| potential undefined behavior in functions | Section 3.4.1 |
| unknown function side-effects | Section 3.4.2 |
| potential runtime exceptions in functions | Section 3.4.3 |
| unknown function return values | Section 3.4.4 |
| externally visible functions | Section 3.4.5 |
| potentially aliasing pointers | Section 3.5.1 |
| potentially escaping pointers | Section 3.5.2 |
| unknown pointer usage | Section 3.5.3 |
| unknown pointer alignment | Section 3.5.4 |
| potentially non-dereferenceable pointers | Section 3.5.5 |
| potentially invariant memory locations | Section 3.5.6 |

| Sec. | 3.1 | 3.1 | 3.1 | 3.2 | 3.3 | 3.4.2 | 3.4.3 | 3.4.4 | 3.4.5 |
|---|---|---|---|---|---|---|---|---|---|
| Det. | **nsw** | **nuw** | **gep** | | | function behavior | | | |
| (A) | 0 | 12 | 0 | 3 | 1 | 5/7 | 2 | 0 | 4 |
| (B) | 0 | 16/22 | 0 | 3 | 1 | 4 | 0 | 0 | 1/3 |
| (C) | 0 | 0 | 0 | 4 | 8/27 | 15/23 | 14 | 0 | 2 |
| (D) | 2 | 16 | 0 | 6 | 0/2 | 3/4 | 1 | 0 | 0 |
| (E) | 0 | 18/19 | 0 | 0 | 0 | 18/37 | 9/14 | 8 | 33/37 |
| (F) | 47 | 132 | 9 | 18 | 3 | 3 | 1 | 0 | 2 |

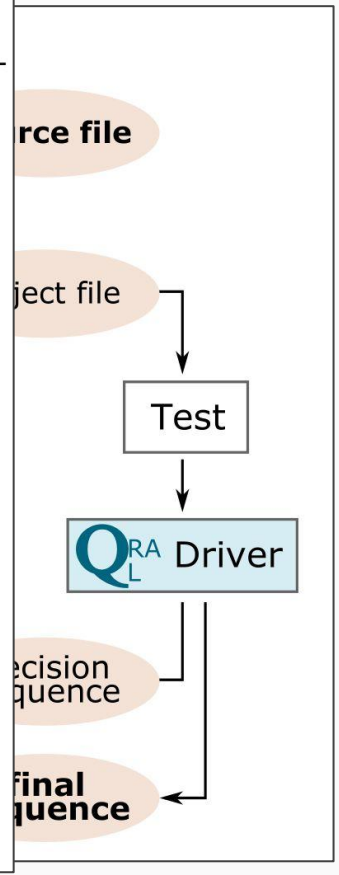
# ORAQL - Perfect Alias Analysis Queries

1) Explore a
local opt

2) Determin
and iden

3) Improve
situation

| Benchmark | Programming Model | ORAQL speedup |
|---|---|---|
| TestSNAP | C++ | 3.6% |
| TestSNAP | C++, OpenMP | 1.0% |
| TestSNAP | C++, Kokkos, CUDA | 0 |
| TestSNAP | Fortran | 5% |
| XSBench | all versions | 0 |
| GridMini | C++, OpenMP Offload | -7% |
| Quicksilver | C++, OpenMP | *[inconclusive]* |
| LULESH | C++ | 0.8% |
| LULESH | C++, OpenMP | 1.4% |
| LULESH | C++, MPI | -0.2% |
| MiniFE | C++, OpenMP | 0 |
| MiniGMG | C, SSE intrinsics | 3.4% |
| MiniGMG | C, OpenMP tasks | 1% |
| MiniGMG | C, OpenMP | 8.3% |




Jan Hueckelh
--- See o

# LLVM/OpenMP - Misc

# Improved OpenMP Offload Error Diagnostic

```
$ clang++ -fopenmp -fopenmp-targets=nvptx64 -O3 -gline-tables-only sum.cpp -o sum
$ ./sum
CUDA error: an illegal memory access was encountered
Libomptarget error: Copying data from device failed.
Libomptarget error: Call to targetDataEnd failed, abort target.
Libomptarget error: Failed to process data after launching the kernel.
Libomptarget error: Consult https://openmp.llvm.org/design/Runtimes.html for debugging options.
sum.cpp:5:1: Libomptarget error 1: failure of target construct while offloading is mandatory
```

See: *Advancing OpenMP Offload Debugging Capabilities in LLVM* (LLPP'21)

# Improved OpenMP GPU Runtime Information

```
$ clang++ -fopenmp -fopenmp-targets=nvptx64 -O3 -gline-tables-only sum.cpp -o sum
$ env LIBOMPTARGET_INFO=$((0x1 | 0x10 | 0x20)) ./sum
Entering OpenMP kernel at sum.cpp:5:1 with 3 arguments:
      firstprivate(N)[8] (implicit)
      tofrom(sum)[8] (implicit)
      to(A[:N])[8192]
Copying data from host to device, Size=8, Name=sum
Copying data from host to device, Size=8192, Name=A[:N]
Launching kernel __omp_offloading_fd02_60a38a2f__Z3sumPdm_l5 with 1 blocks and 128 threads in SPMD mode
```

See: *Advancing OpenMP Offload Debugging Capabilities in LLVM* (LLPP'21)

# Improved OpenMP GPU Runtime Checks

```
$ clang++ -fopenmp -fopenmp-targets=nvptx64 -fopenmp-target-debug=0x5 sum.cpp -o sum
$ env LIBOMPTARGET_DEVICE_RTL_DEBUG=0x5 ./sum
Shared memory stack full, fallback to dynamic allocation of global memory will negatively impact performance.
nullptr returned by malloc!
CUDA error: an illegal memory access was encountered
```

See: Co-Designing an OpenMP GPU Runtime and Optimizations (IPDPS'21)

# Remarks & Assumptions - Interactive Optimization

OpenMP-Opt emits remarks:

- -Rpass=openmp-opt
- -Rpass-missed=openmp-opt
- -Rpass-analysis=openmp-opt

to report success and failure,

and utilizes assumptions:

- `#pragma omp assumes ...`
- `__attribute__((assume("...")))`
- command line flags

to enhance static analysis.

*New* environment assumptions:
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```

LLVM assumption extensions:

```
ompx_spmd_amenable
ompx_aligned_barrier
ompx_no_sync
```

```
-fopenmp-cuda-mode
-fopenmp-assume-no-nested-parallelism
-fopenmp-assume-no-thread-state
-fopenmp-assume-teams-oversubscription
-fopenmp-assume-threads-oversubscription
```

# Example: LLVM Remarks

## OpenMP Optimization Remarks

The OpenMP-Aware optimization pass is able to generate compiler remarks for performed and missed optimisations. To emit them, pass these options to the Clang invocation: `-Rpass=openmp-opt -Rpass-analysis=openmp-opt -Rpass-missed=openmp-opt`. For more information and features of the remark system, consult the clang documentation:

- Clang options to emit optimization reports
- Clang diagnostic and remark flags
- The -foptimization-record-file flag and the -fsave-optimization-record flag

### OpenMP Remarks

| Diagnostics Number | Diagnostics Kind | Diagnostics Description |
|---|---|---|
| OMP100 | Analysis | Potentially unknown OpenMP target region caller. |
| OMP101 | Analysis | Parallel region is used in unknown / unexpected ways. Will not attempt to rewrite the state machine. |
| OMP102 | Analysis | Parallel region is not called from a unique kernel. Will not attempt to rewrite the state machine. |
| OMP110 | Optimization | Moving globalized variable to the stack. |
| OMP111 | Optimization | Replaced globalized variable with X bytes of shared memory. |
| OMP112 | Missed | Found thread data sharing on the GPU. Expect degraded performance due to data globalization. |
| OMP113 | Missed | Could not move globalized variable to the stack. Variable is potentially captured in call. Mark parameter as *__attribute__((noescape))* to override. |
| OMP120 | Optimization | Transformed generic-mode kernel to SPMD-mode. |
| OMP121 | Analysis | Value has potential side effects preventing SPMD-mode execution. Add *__attribute__((assume("ompx_spmd_amenable")))* to the called function to override. |
| OMP130 | Optimization | Removing unused state machine from generic-mode kernel. |
| OMP131 | Optimization | Rewriting generic-mode kernel with a customized state machine. |
| OMP132 | Analysis | Generic-mode kernel is executed with a customized state machine that requires a fallback. |
| OMP133 | Analysis | Call may contain unknown parallel regions. Use *__attribute__((assume("omp_no_parallelism")))* to override. |
| OMP140 | Analysis | Could not internalize function. Some optimizations may not be possible. |
| OMP150 | Optimization | Parallel region merged with parallel region at <location>. |
| OMP160 | Optimization | Removing parallel region with no side-effects. |
| OMP170 | Optimization | OpenMP runtime call <call> deduplicated. |
| OMP180 | Optimization | Replacing OpenMP runtime call <call> with <value>. |
| OMP190 | Optimization | Redundant barrier eliminated. (device only) |

```
for (int i = 0; i < j; i++)
  x_val -= x_ptr[i] * G_ptr[i]
```

```
$ clang++ -fopenmp -Rpass-ana
remark: loop not vectorized:
```

```
void work(void *);
void foo() {
  int local;
  work(&local);
}
#pragma omp declare target(foo)
```

```
$ clang++ -fopenmp -fopenmp-t
remark: Could not move globali
parameter as __attribute__((n
```

```
p simd
< j; i++)
tr[i] * G_ptr[i]
```

```
perations
```

```
ttribute__((noescape)) void *);
;
 declare target(foo)
```

```
op -O2
 captured in call. Mark
```

# Multi-architecture Binaries

- LLVM now supports compiling for many architectures
  - Allows the same binary to run on several machines
- Without --fopenmp-targets we will try to infer the triples

```
$ clang app.c -fopenmp -fopenmp-targets=nvptx64,amdgcn -c \
     -Xopenmp-target=nvptx64 --offload-arch=sm_80         \
     -Xopenmp-target=amdgcn --offload-arch=gfx90a
$ clang app.c -fopenmp --offload-arch=sm_80 --offload-arch=gfx90a -c
$ llvm-readelf -S app.o
Section Headers:
[Nr] Name              Type            Address          Off    Size   ES Flg Lk Inf Al
[11] .llvm.offloading LLVM_OFFLOADING 0000000000002058 002058 0024c0 00 E   0  0   8
[12] omp_offloading_entries PROGBITS  0000000000005048 004048 000020 00 A   0  0   8
```

Slide originally by *Joseph Huber*

# Multi-architecture Binaries

Can inspect the embedded device code with binary utils

```
$ clang app.c -fopenmp --offload-arch=sm_80 --offload-arch=gfx90a -o app
$ llvm-objdump --offloading ./app
OFFLOADING IMAGE [0]:
kind elf
arch gfx90a
triple amdgcn-amd-amdhsa
producer openmp

OFFLOADING IMAGE [1]:
kind elf
arch sm_80
triple nvptx64-nvidia-cuda
producer openmp
```

Slide originally by *Joseph Huber*

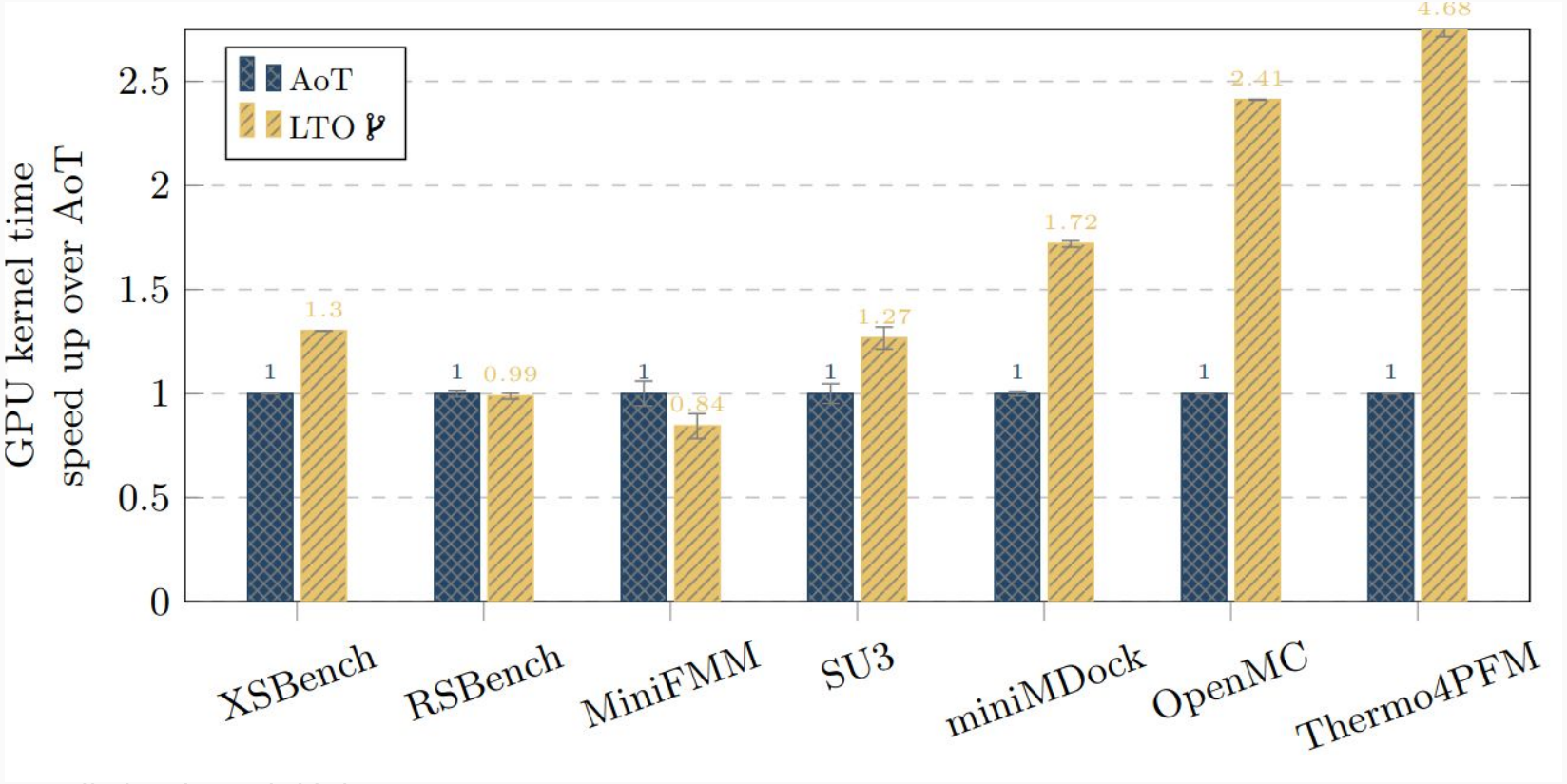
# Link Time Optimization (LTO)

- Compilers normally optimize a single translation unit (TU) at a time
  - LTO allows the compiler to optimize the whole program
- LLVM now supports LTO for the device
- Currently needs to be specified for both

```
$ clang app.c -fopenmp -fopenmp-targets=nvptx64 -foffload-lto -O3 -c
$ clang app.o -fopenmp -fopenmp-targets=nvptx64 -foffload-lto -O3
```

Slide originally by *Joseph Huber*

# LTO Performance Improvement (A100 Nvidia GPU)




Slide originally by *Joseph Huber*

# Static Library Support

- LLVM now completely supports static libraries
  - Any method of creating static libraries should work now
- The linker only imports used symbols from static libraries
  - Somewhat inherit this behaviour for multi-architecture binaries

```
$ clang foo.c -fopenmp --offload-arch=sm_70 --offload-arch=sm_80 --offload-arch=gfx908 -c
$ llvm-ar rcs libfoo.a foo.o
$ clang app.c -fopenmp --offload-arch=sm_70 -lfoo -o app
$ llvm-objdump --offloading
OFFLOADING IMAGE [0]:
kind elf
arch sm_70
triple nvptx64-nvidia-cuda
producer openmp
```

Slide originally by *Joseph Huber*

# Static Library Support

Can use this to create generic libraries, with LTO -> zero runtime overhead

```
#pragma omp begin declare target device_type(nohost)

#pragma omp begin declare variant match(...)
void foo() {...}
#pragma omp end declare variant

#pragma omp end declare target
```

```
$ clang device.c -c -fopenmp --offload-arch=sm_52,sm_70,sm_80,gfx908,gfx90a,gfx90c -O3 \
    -foffload-lto -fvisibility=hidden -fopenmp-cuda-mode
$ llvm-ar rcs libdevice.a device.o
$ clang app.c -fopenmp --offload-arch=sm_80 -foffload-lto -ldevice
```

Slide originally by *Joseph Huber*

# CUDA / HIP Interoperability

- The new driver can compile both CUDA and HIP
  - Requires explicitly using the new Driver
- LLVM now supports CUDA compilation in RDC-mode
  - Previously required external build systems

```
$ clang++ cuda.cu util.cu -fgpu-rdc --offload-arch=sm_70 --offload-new-driver -c
$ clang++ cuda.o util.o --offload-link -lcudart -o app
$ ./a.out
```

Slide originally by *Joseph Huber*

# CUDA / HIP Interoperability

OpenMP interoperability with CUDA/HIP

- Caveat: Global state is not yet shared; would require having state registered by OpenMP *or* CUDA

```
void openmp() { printf ("Hello from OpenMP\n"); }
#pragma omp declare target device_type(nohost) to(openmp)

__device__ cuda() { printf ("Hello from CUDA\n"); }
```

```
$ clang++ cuda.cu -fgpu-rdc --offload-arch=sm_70 --offload-new-driver -c
$ clang++ openmp.cpp -fopenmp --offload-arch=sm_70 -c
$ clang++ cuda.o openmp.o -fopenmp -fopenmp-targets=nvptx64 -lcudart
./a.out
Hello from OpenMP
Hello from CUDA
```

Slide originally by *Joseph Huber*

# Device Only Compilation

- Device only compilation to output the device code
- Mainly useful for inspecting output

```
$ clang app.c -fopenmp --offload-arch=sm_70 -S -emit-llvm --offload-device-only -o -
< LLVM IR >
```

Slide originally by *Joseph Huber*

# Mandatory Offloading

- OpenMP offloading supports host-fallback by default
- This requires emitting each device function on the host
- Can be disabled using a command line flag
  - Makes interoperability with CUDA easier.

```
$ clang app.c -fopenmp --offload-arch=sm_70 -fopenmp-offload-mandatory
```

Slide originally by *Joseph Huber*

# Latest LLVM Release

LLVM 15 has been released and contains various new offloading features, incl.

- A new compiler driver for offloading (OpenMP, CUDA, HIP)
- Multi-Architecture binaries
- Link Time Optimization
- Static Library Support
- OpenMP and CUDA / HIP interoperability
- Extra flags improving offloading performance

Slide originally by *Joseph Huber*

# Per-Kernel Dynamic Shared Memory

- Dynamic shared memory allocated by the kernel (CUDA/HIP style)
  - Size determined at runtime
  - Works on AMD and NVIDIA GPUs
  - See https://openmp.llvm.org/design/Runtimes.html#libomptarget-dynamic-shared

```
#pragma omp target teams ... ompx_dyn_cgroup_mem(4 * N)
{
   float *SharedBuffer = llvm_omp_target_dynamic_shared_alloc()
   compute(A, SharedBuffer, N);
}
```

# (Basic) GPU JIT

- Optimize and finalize GPU images (stored as IR) at runtime

```
$ clang app.c -fopenmp --fopenmp-target-jit --offload-arch=native -O3 -foffload-lto
$ LIBOMPTARGET_JIT_OPT_LEVEL=2 ./a.out
```

- Inspect, modify, and replace the image (IR or object file)
  - See https://openmp.llvm.org/design/Runtimes.html#libomptarget-jit-replacement-object

```
$ LIBOMPTARGET_JIT_PRE_OPT_IR_MODULE=pre_jit_opt.ll ./a.out
$ LIBOMPTARGET_JIT_POST_OPT_IR_MODULE=post_jit_opt.ll ./a.out
$ LIBOMPTARGET_JIT_REPLACEMENT_MODULE=modified_ir.ll ./a.out
$ LIBOMPTARGET_JIT_REPLACEMENT_OBJECT=image.o ./a.out
```

Work by Shilei Tian (SBU)

# Record and Replay for Kernels

- Extract kernels for standalone execution
  - Composes with JIT
  - Allows isolated debugging, profiling, (manual) tuning, …
  - Certain features are only available after 16, e.g., usage of globals
  - See: https://github.com/llvm/llvm-project/blob/llvmorg-16.0.0-rc1/openmp/docs/ReleaseNotes.rst

```
$ LIBOMPTARGET_RECORDING=True LIBOMPTARGET_RR_SAVE_OUTPUT=True ./a.out
$ llvm-omp-kernel-replay <kernel_recording_file.json>
```

Work by Giorgis Georgakoudis (LLNL) and Steve Rangel (ANL)

# Latest LLVM Release

LLVM 16 has been released and contains various new offloading features, incl.

- Asynchronous AMD GPU offloading
- JIT support (-fopenmp-target-jit)
- Record and Replay
- --offload-arch=native
- Performance improvements

Slide originally by *Joseph Huber*

# Work in Progress — Selection

- OpenMP equivalent to “launch bounds" (CUDA) or kernel attributes, e.g., “waves-per-eu”, (AMD)
- Portability layer to access native functionality (e.g., Thrust, or shuffle)
- “Bare-metal” kernels → “CUDA-style kernel programming” (w/o overhead)
- New (=fast) GPU reductions
- Libc and libc++ support for GPUs
- Intel (ARM, Apple) GPU support
- 3-level parallelism (aka. “Proper” SIMD support)
- “omp loop” support

# LLVM/OpenMP Device Info

# llvm-omp-device-info

A command line utility that, by using `libomptarget`, and the device plugins, list devices information as seen from the OpenMP Runtime.

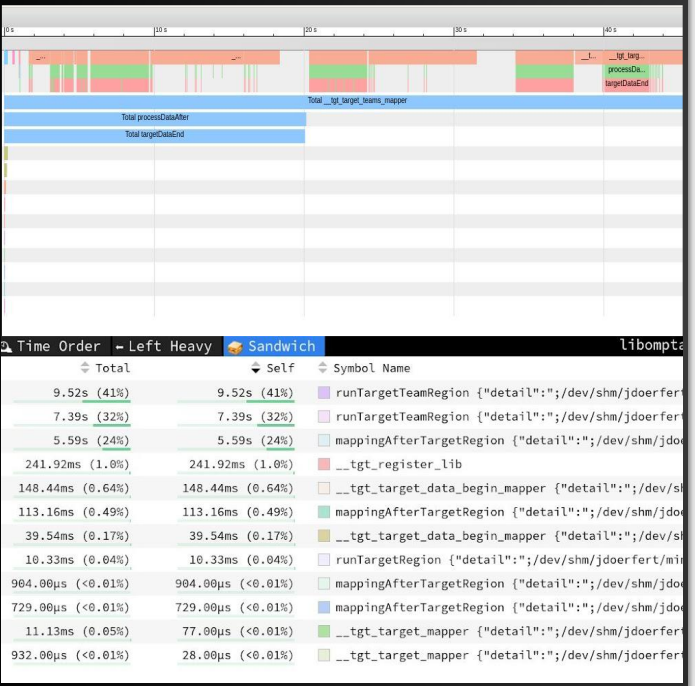
```
➜  ./llvm-omp-device-info
Device (0):
    print_device_info not implemented
...

Device (4):
    CUDA Driver Version:                11040
    CUDA Device Number:                 0
    Device Name:                        NVIDIA GeForce RTX 2080
    Global Memory Size:                 4294967295 bytes
    Number of Multiprocessors:          46
    Concurrent Copy and Execution:      Yes
    Total Constant Memory:              65536 bytes
    Max Shared Memory per Block:        49152 bytes
    Registers per Block:                65536
    Warp Size:                          32 Threads
    Maximum Threads per Block:          1024
    Maximum Block Dimensions:           1024, 1024, 64
    Maximum Grid Dimensions:            2147483647 x 65535 x 65535
    Maximum Memory Pitch:               2147483647 bytes
    Texture Alignment:                  512 bytes
    Clock Rate:                         1710000 kHz
    Execution Timeout:                  No
    Integrated Device:                  No
    Can Map Host Memory:                Yes
    Compute Mode:                       DEFAULT
    Concurrent Kernels:                 Yes
    ECC Enabled:                        No
    Memory Clock Rate:                  7000000 kHz
    Memory Bus Width:                   256 bits
    L2 Cache Size:                      4194304 bytes
    Max Threads Per SMP:                1024
    Async Engines:                      Yes (3)
    Unified Addressing:                 Yes
    Managed Memory:                     Yes
    Concurrent Managed Memory:          Yes
    Preemption Supported:               Yes
    Cooperative Launch:                 Yes
    Multi-Device Boars:                 No
    Compute Capabilities:               75
```

Credit to *Jose Monsalve Diaz* (ANL).

# LLVM/OpenMP Target Profiling

# Chrome Profiling Traces




*LLVM 12 introduced*

*LIBOMPTARGET_PROFILE=file.json*

*to portably track target interaction.*

*Chrome tracing format, source line information, …*

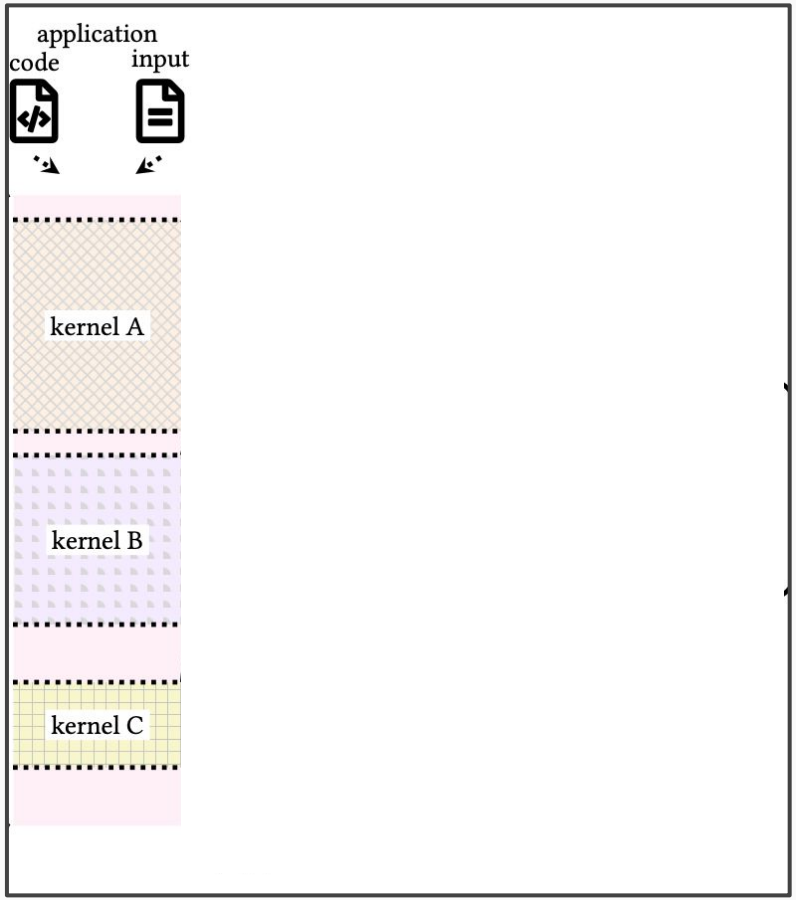
*https://openmp.llvm.org/docs/design/Runtimes.html#libomptarget-profile*

***Basic kernel profiling PoC available, including user-defined regions!***

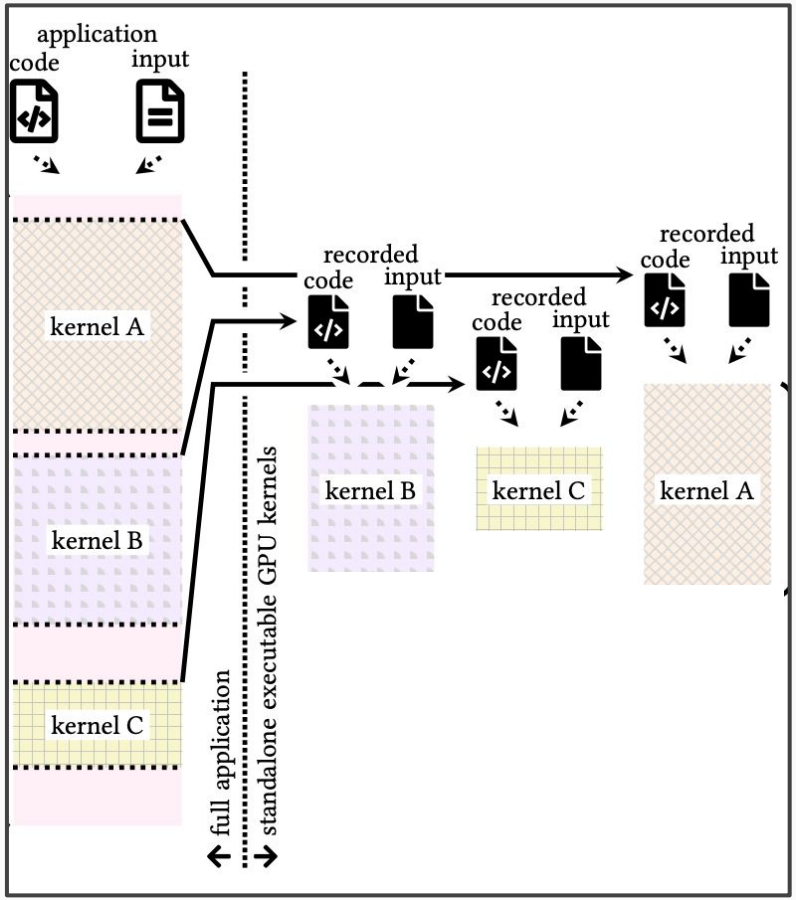
Credit to Giorgis Georgakoudis (LLNL) and Neeraj Rajesh (IIT).

# LLVM/OpenMP Record-and-Replay

# llvm-omp-kernel-replay

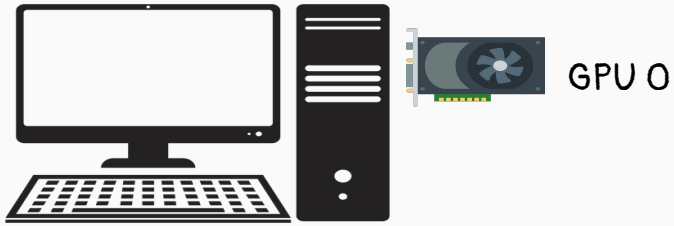


# llvm-omp-kernel-replay

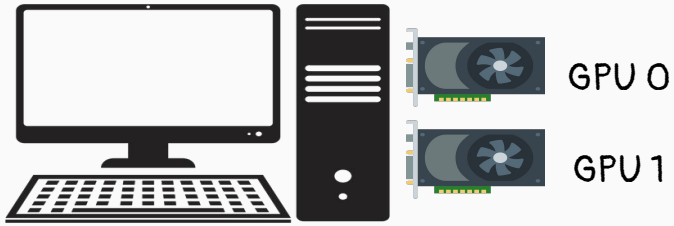


# Remote OpenMP Offloading

# Remote OpenMP Offloading (Plugin)



# Remote OpenMP Offloading (Plugin)

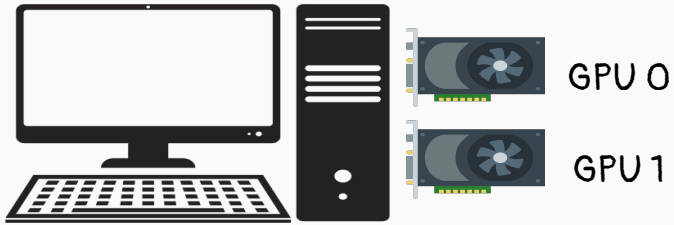


# Remote OpenMP Offloading (Plugin)

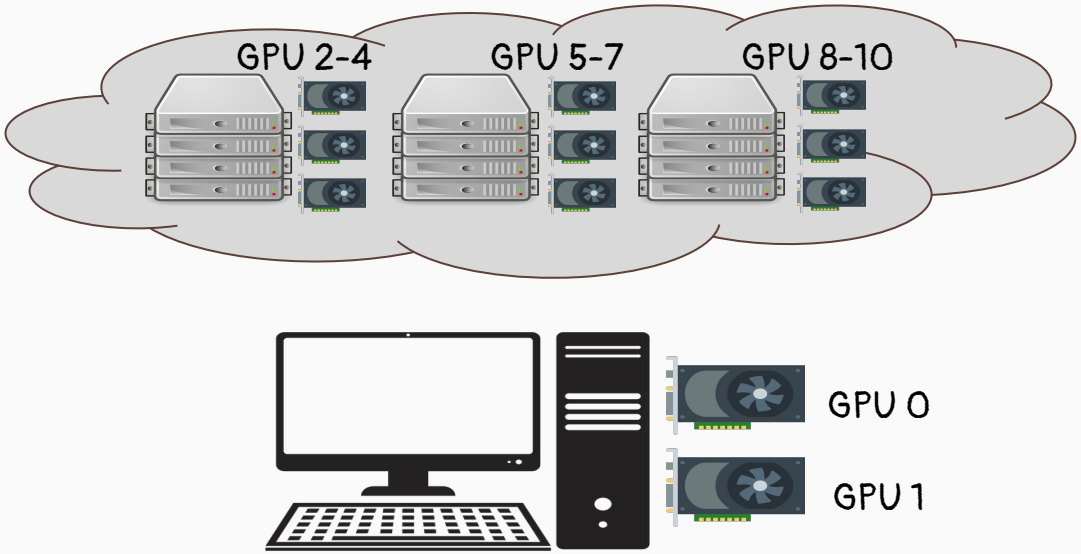
```
#pragma omp parallel for num_threads(num_devices)
for (auto K = 0; K < num_devices; K++) {
    #pragma omp target ... device(K)
    for (auto i = 0; i < lookups_per_device; i++) {

        ...

    }
}
```

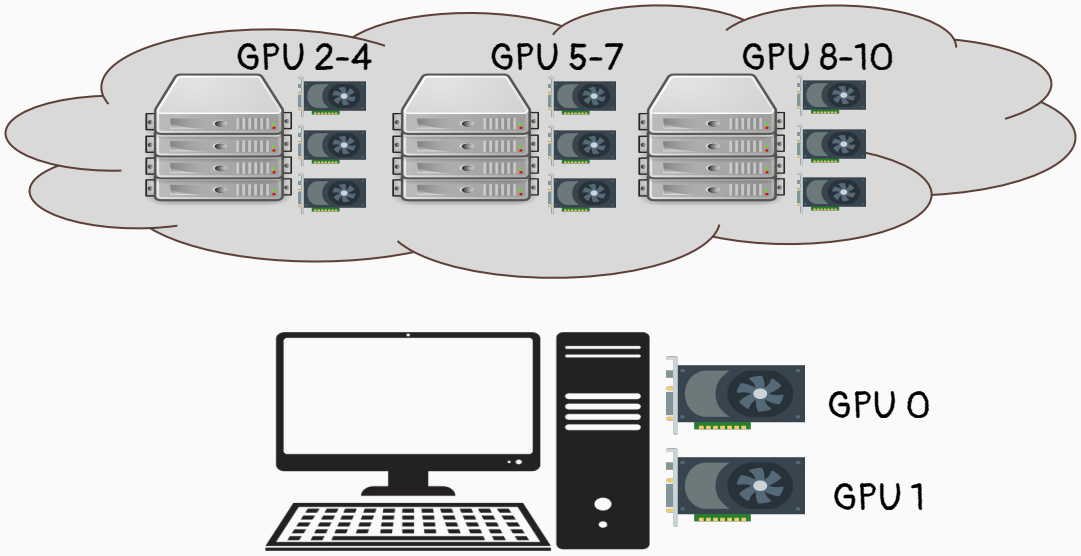


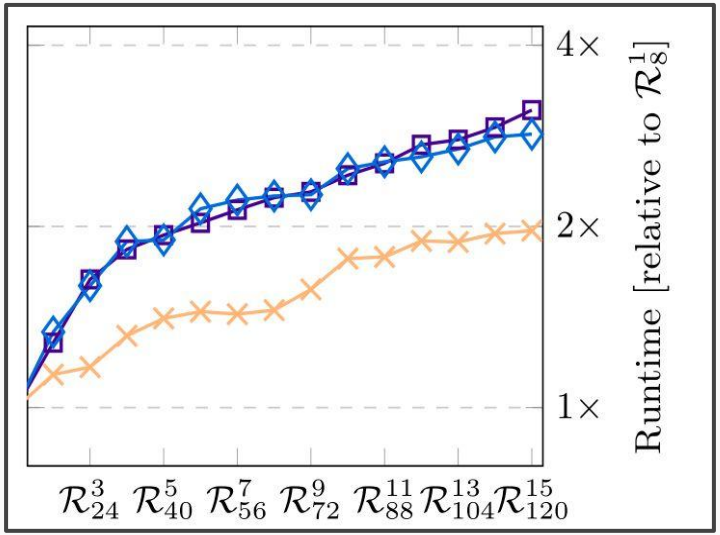
# Remote OpenMP Offloading (Plugin)




See: *Remote OpenMP Offloading* (ISC'22, **best paper**)

# Remote OpenMP Offloading (Plugin)




XSBench - scaling up to
15x8 A100 GPUs compared to 1x8

See: *Remote OpenMP Offloading* (ISC'22, **best paper**)

# Not OpenMP

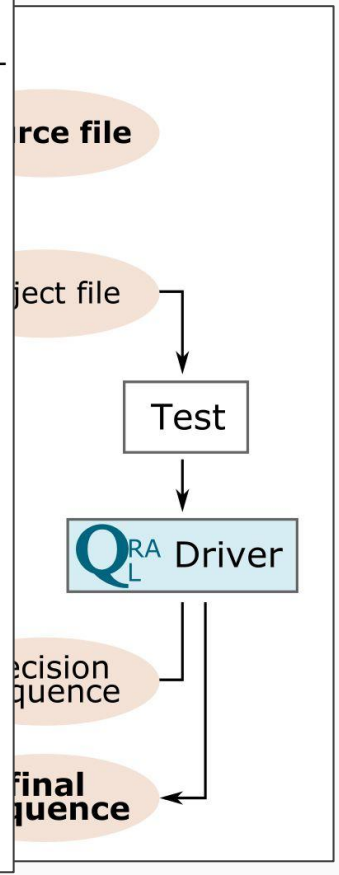
# ORAQL - Perfect Alias Analysis Queries

1) Explore a
local opt

2) Determin
and iden

3) Improve
situation

| Benchmark | Programming Model | ORAQL speedup |
|---|---|---|
| TestSNAP | C++ | 3.6% |
| TestSNAP | C++, OpenMP | 1.0% |
| TestSNAP | C++, Kokkos, CUDA | 0 |
| TestSNAP | Fortran | 5% |
| XSBench | all versions | 0 |
| GridMini | C++, OpenMP Offload | -7% |
| Quicksilver | C++, OpenMP | *[inconclusive]* |
| LULESH | C++ | 0.8% |
| LULESH | C++, OpenMP | 1.4% |
| LULESH | C++, MPI | -0.2% |
| MiniFE | C++, OpenMP | 0 |
| MiniGMG | C, SSE intrinsics | 3.4% |
| MiniGMG | C, OpenMP tasks | 1% |
| MiniGMG | C, OpenMP | 8.3% |

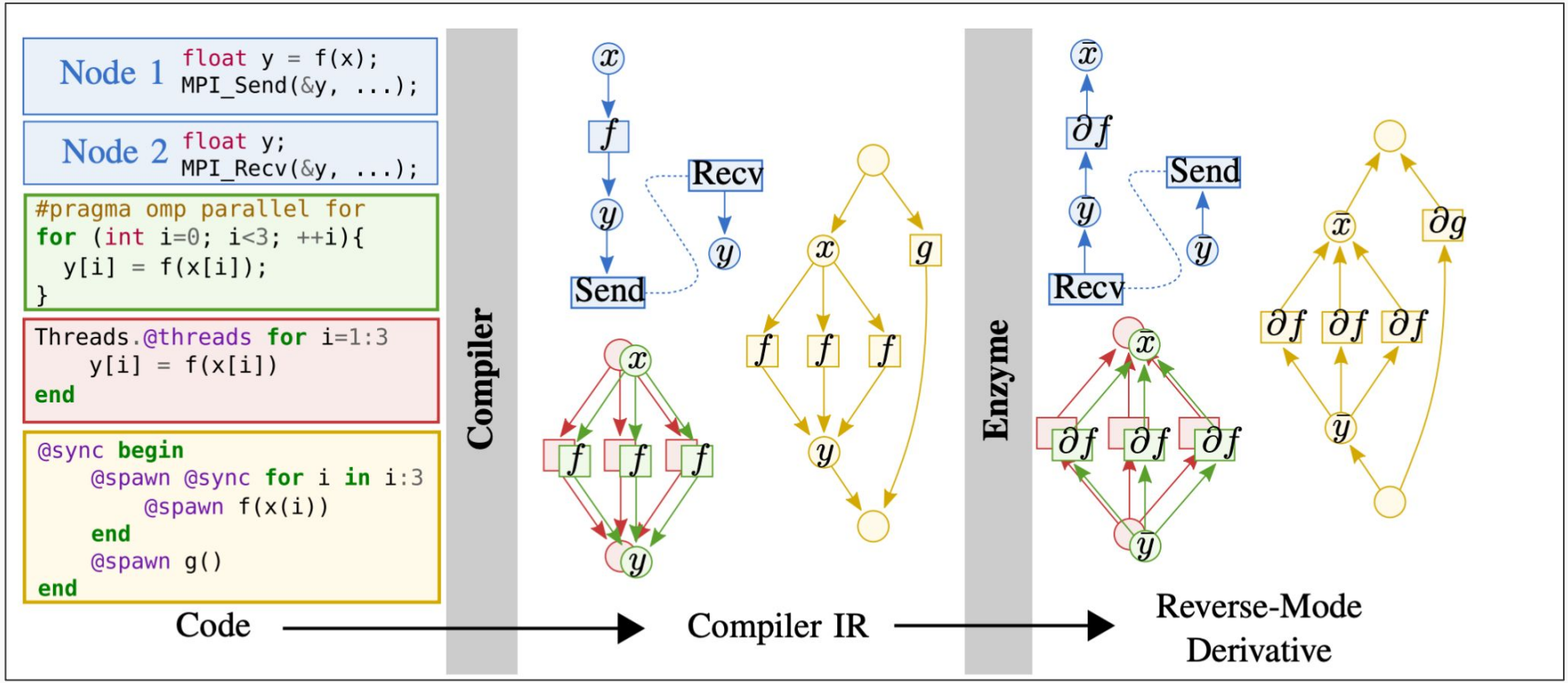



Jan Hueckelh
--- See o

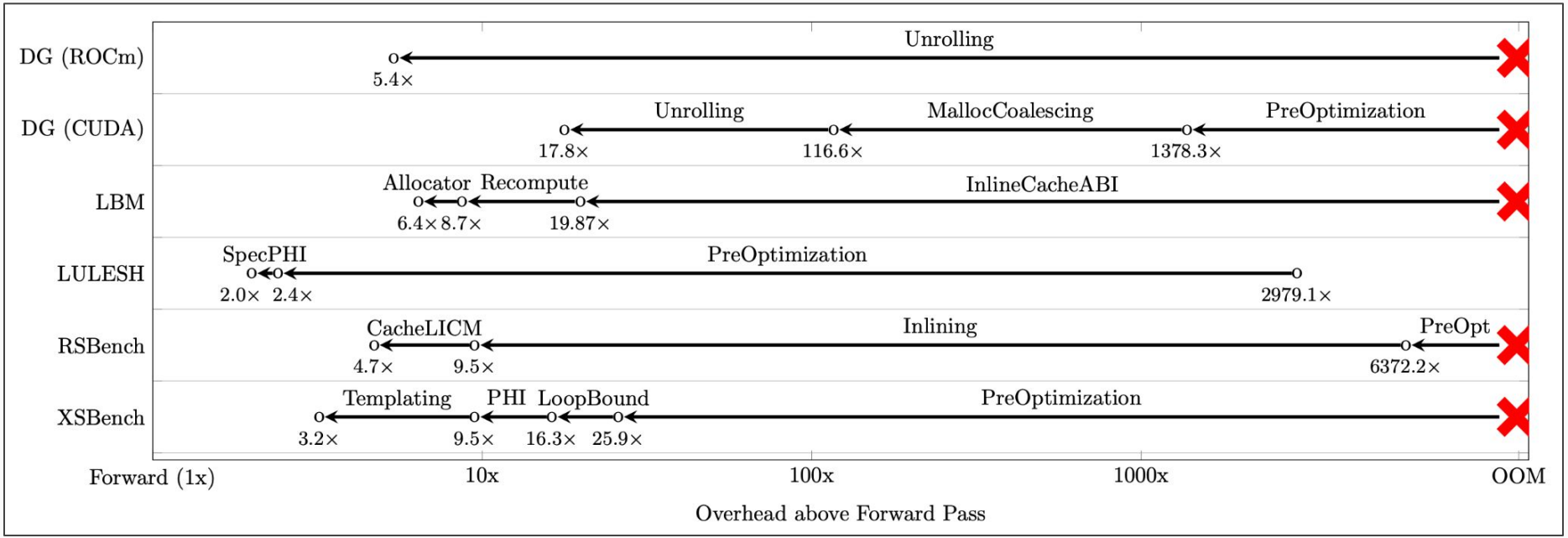
# Automatic Differentiation (AD) without Python/ML/JAX*

* Or other domain specific languages (DSLs).

# Enzyme AD
# Automatic Compiler-Based Differentiation of HPC Codes

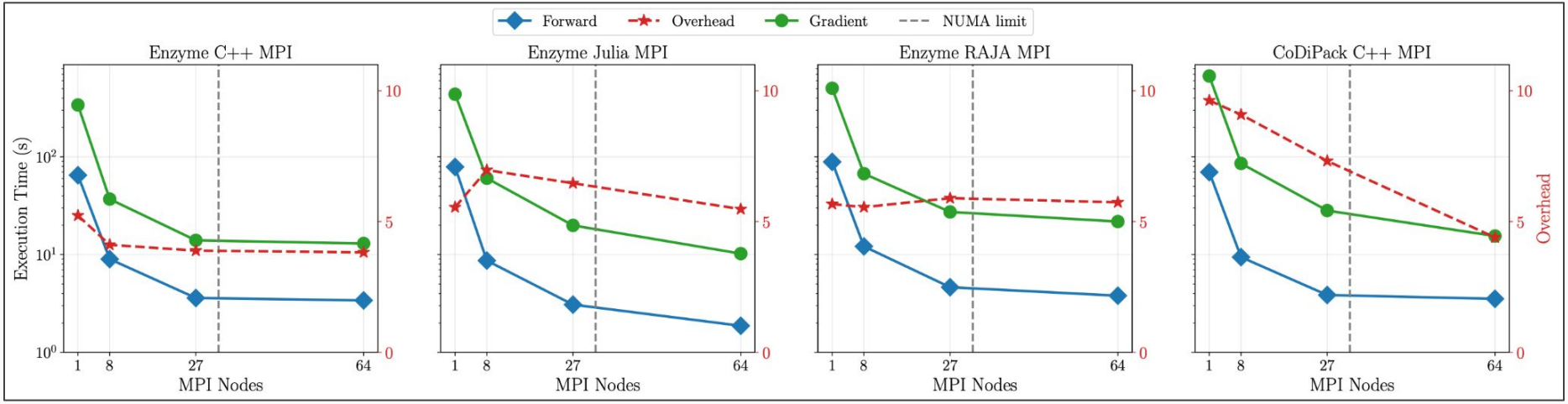



Moses, William, and Valentin Churavy. "*Instead of rewriting foreign code for machine learning, automatically synthesize fast gradients*." Advances in Neural Information Processing Systems (NeurIPS). 2020




Moses, William S., et al. "*Reverse-mode automatic differentiation and optimization of GPU kernels via Enzyme.*" High Performance Computing, Networking, Storage and Analysis (SC). 2021

# Enzyme AD
# Automatic Compiler-Based Differentiation of HPC Codes




Moses, William S., et al. "*Scalable automatic differentiation of multiple parallel paradigms through compiler augmentation*." High Performance Computing, Networking, Storage and Analysis (SC). 2022

# AMA: Ask Me Anything

# Brief Recap & Outlook

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**Enhanced GPU Debugging & Profiling**

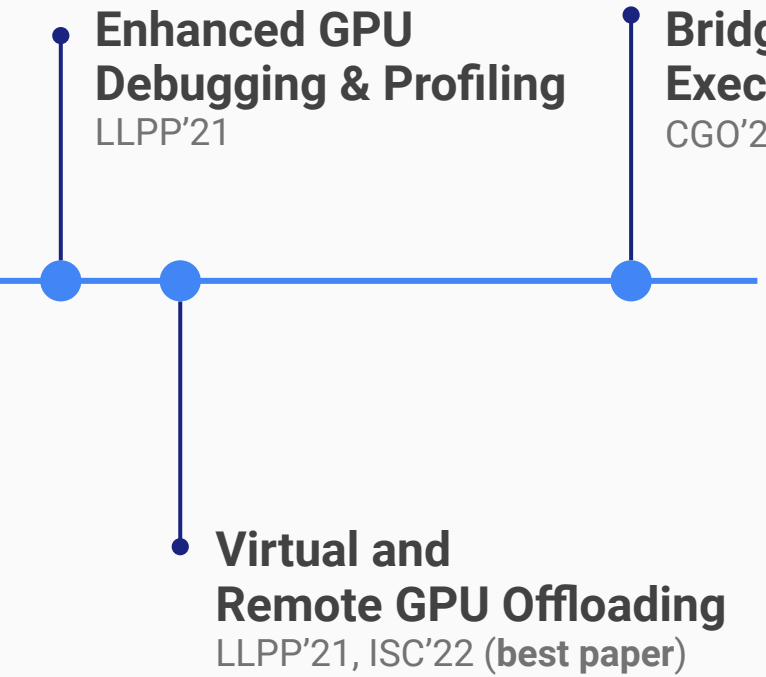
LLPP'21

# Brief Recap

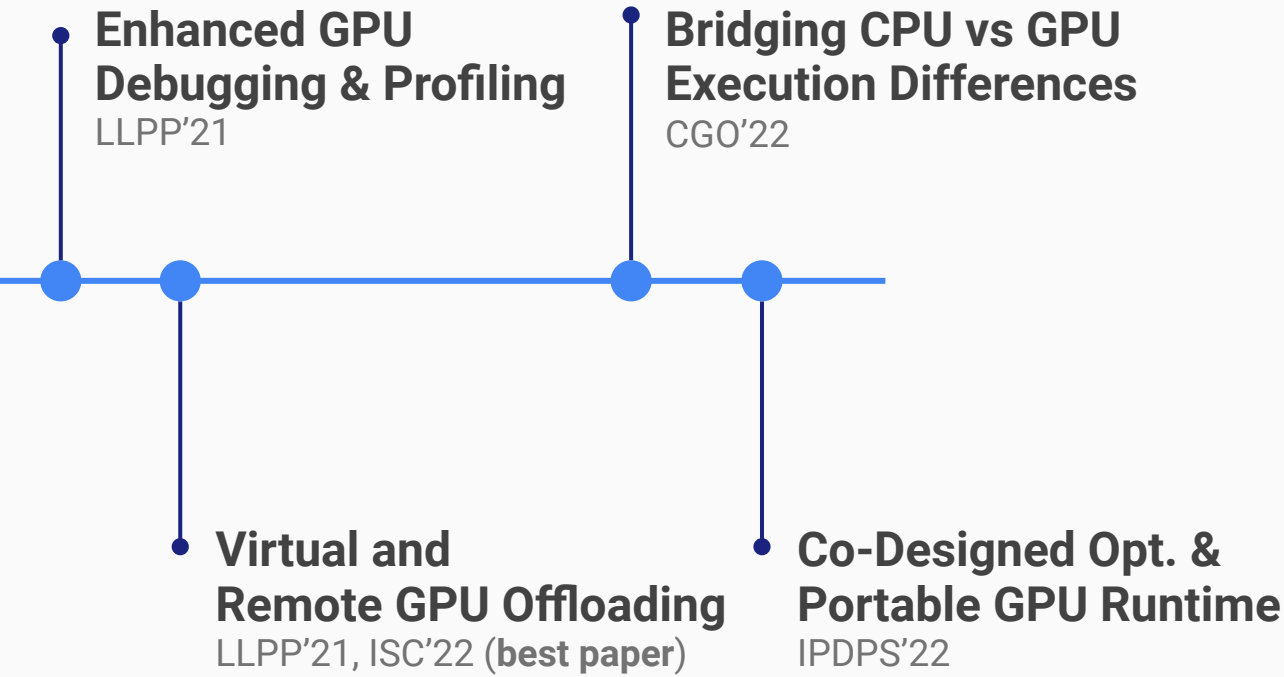
**Enhanced GPU Debugging & Profiling**
LLPP'21

**Virtual and Remote GPU Offloading**
LLPP'21, ISC'22 (**best paper**)

# Brief Recap


Enhanced GPU Debugging & Profiling
LLPP'21
Bridging CPU vs GPU Execution Differences
CGO'22
Virtual and Remote GPU Offloading
LLPP'21, ISC'22 (best paper)

# Brief Recap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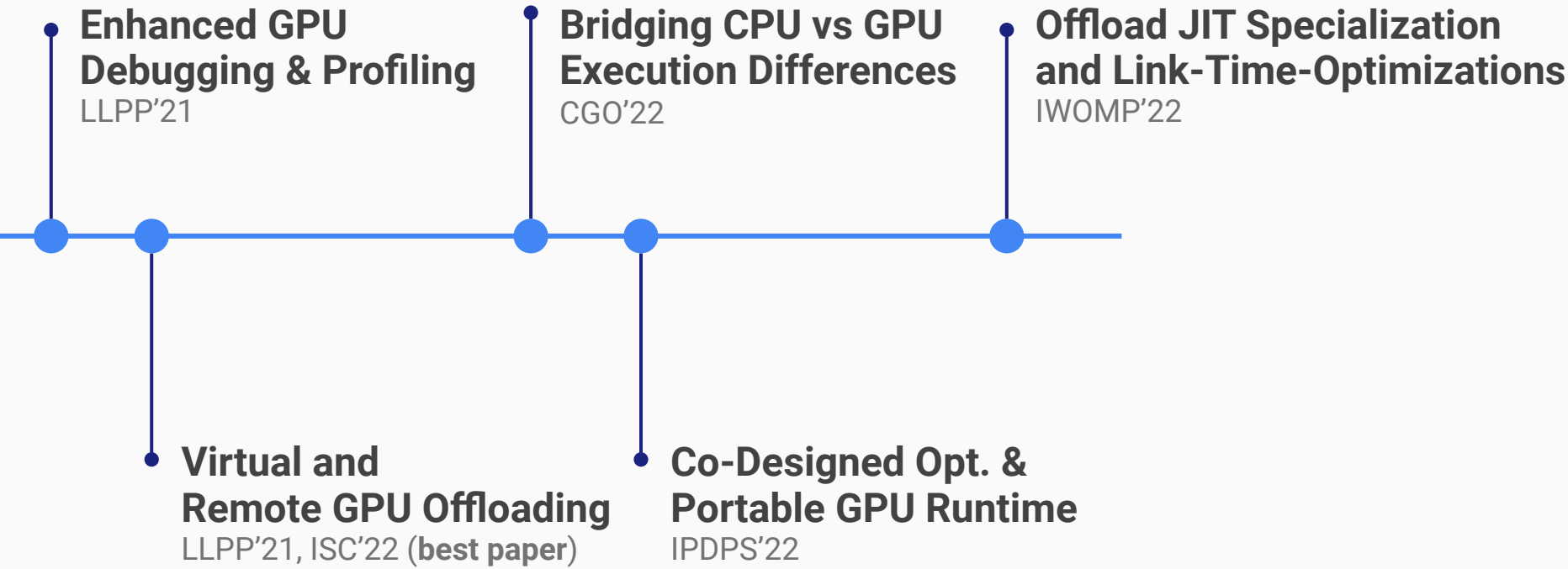
Co-Designed Opt. & Portable GPU Runtime
IPDPS'22

# Brief Recap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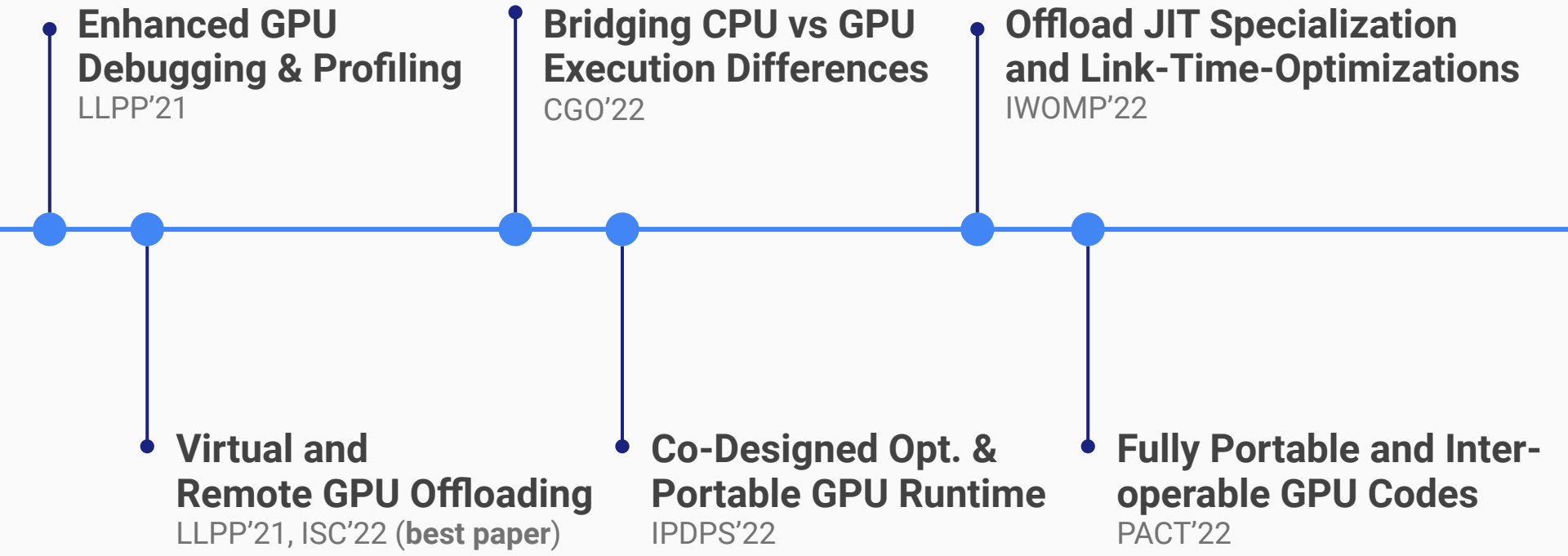
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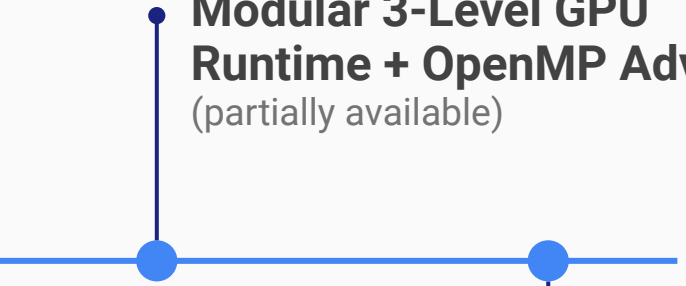
Offload JIT Specialization and Link-Time-Optimizations
IWOMP'22
Fully Portable and Inter-operable GPU Codes
PACT'22

# Brief Outlook

**Modular 3-Level GPU Runtime + OpenMP Advisor**
(partially available)

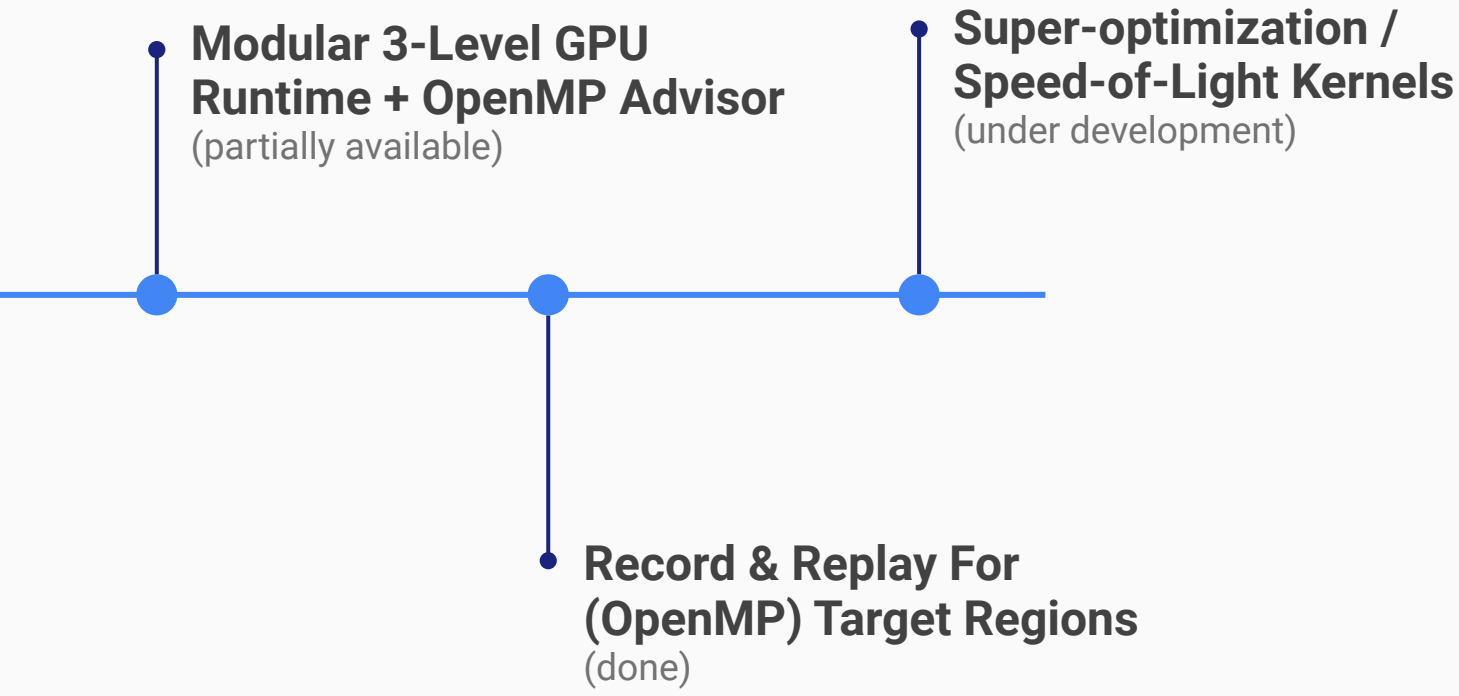
# Brief Outlook



**Modular 3-Level GPU Runtime + OpenMP Advisor**
(partially available)

**Record & Replay For (OpenMP) Target Regions**
(done)

# Brief Outlook



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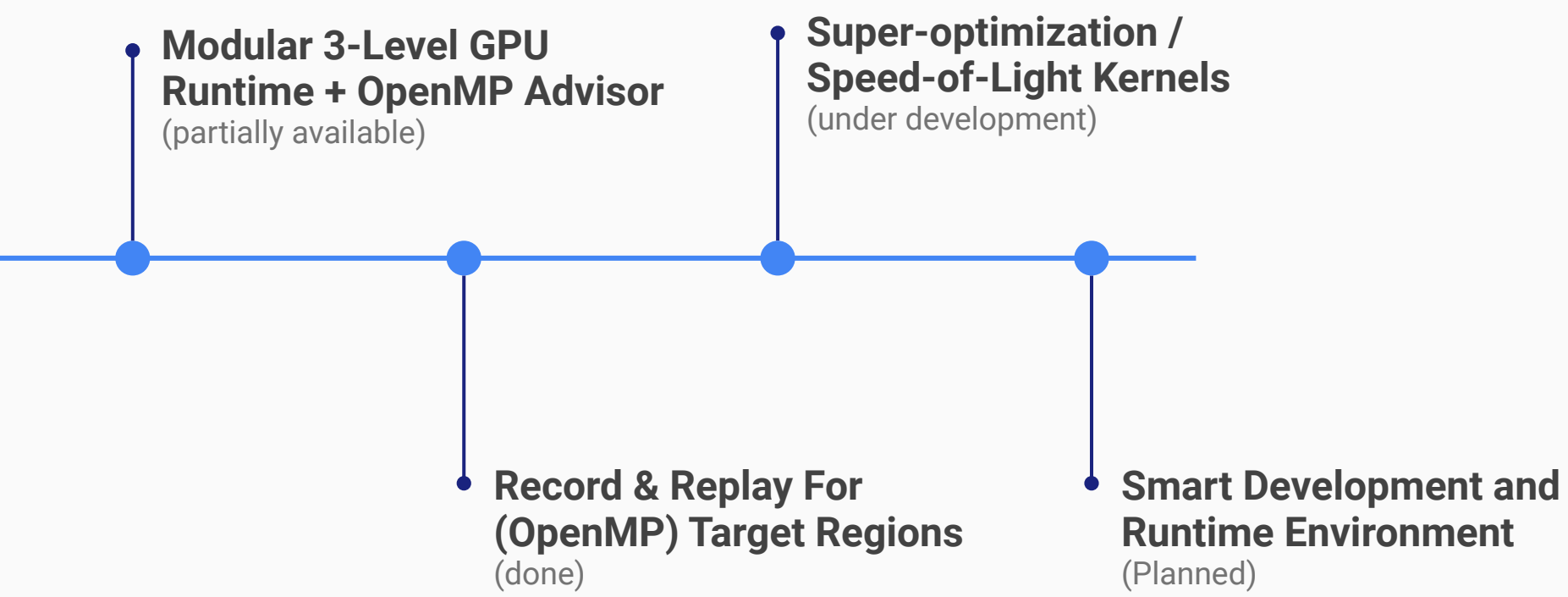

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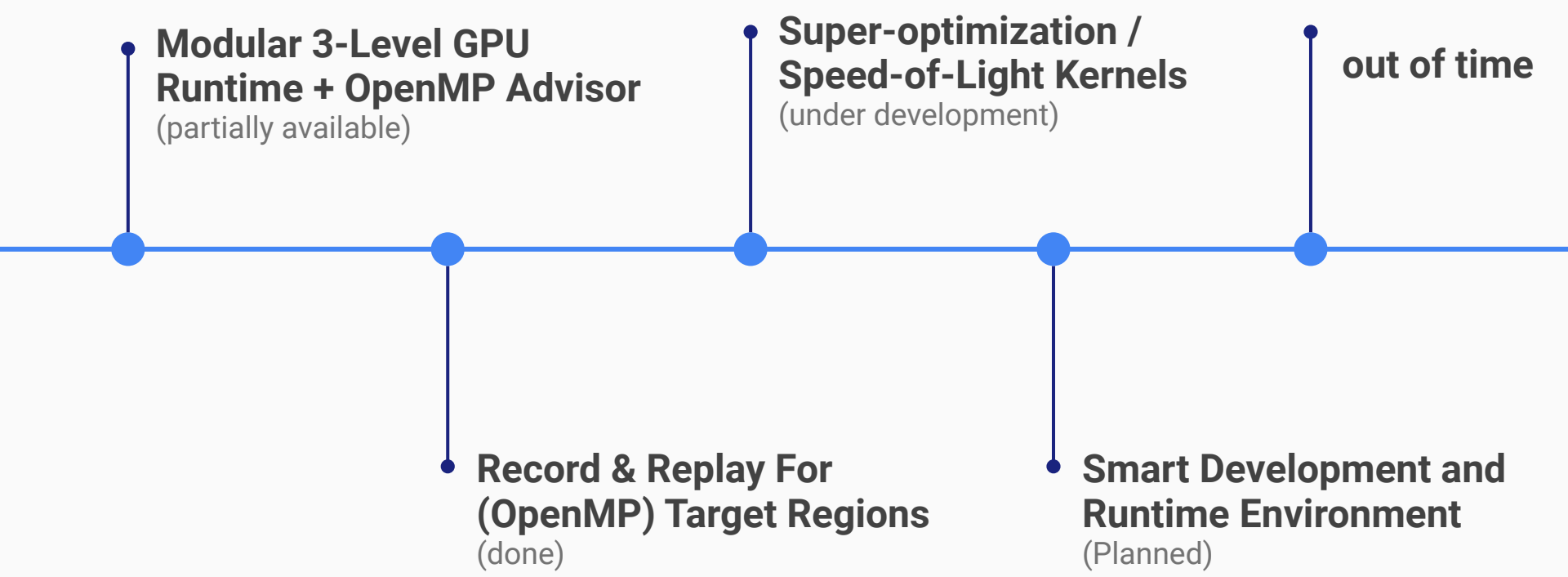
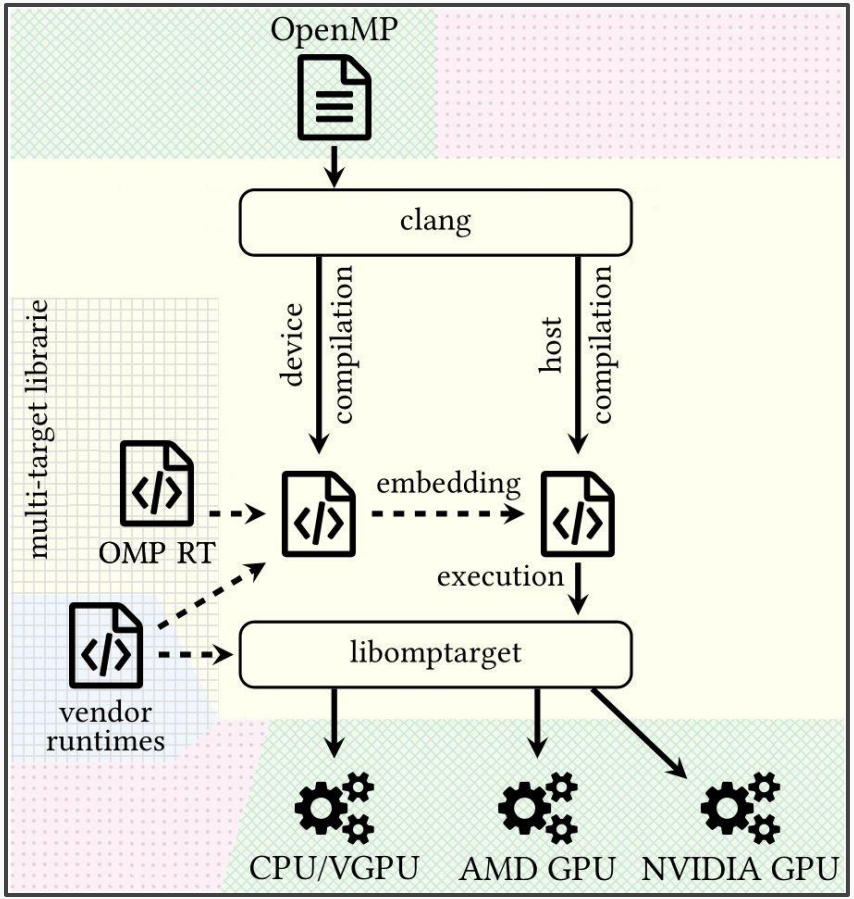


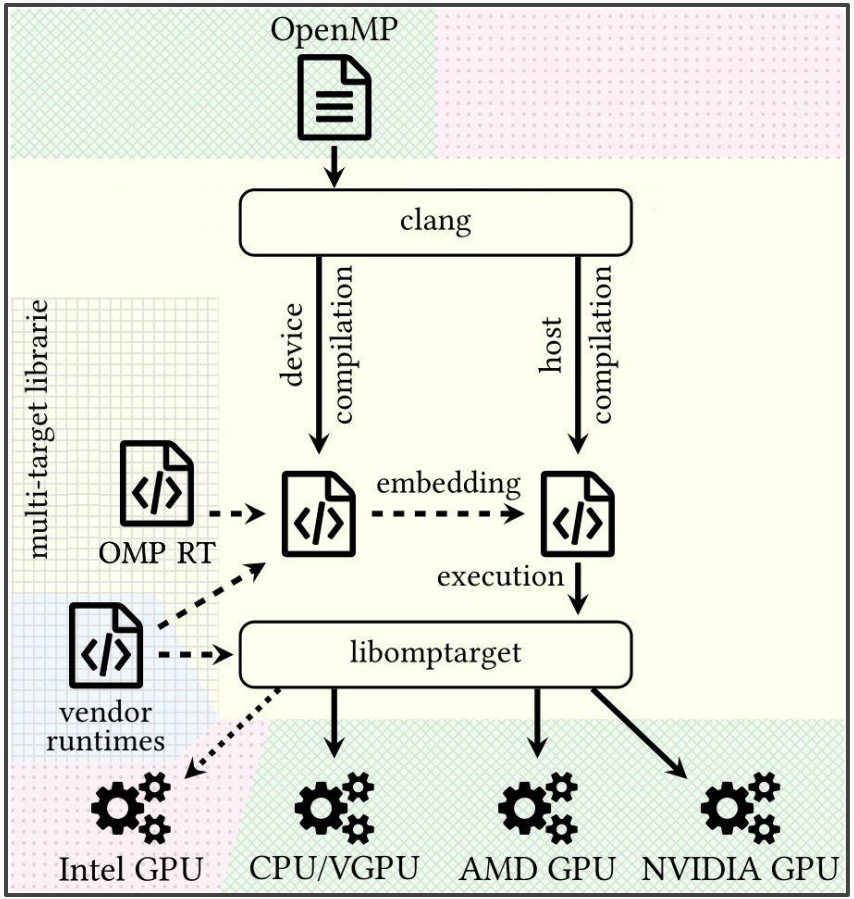
# OpenMP as Intermediate Layer

# LLVM/OpenMP Target Offloading



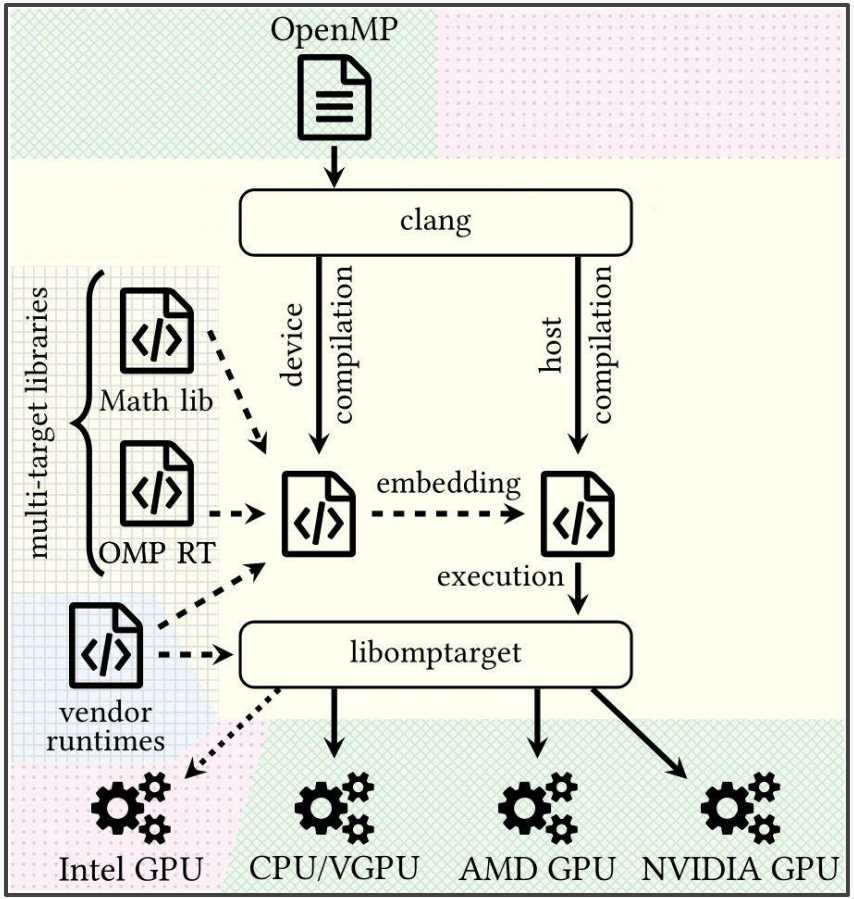

- OpenMP offload code compilation for CPUs, virtual GPU (VGPU), AMD and NVIDIA GPUs

# LLVM/OpenMP Target Offloading



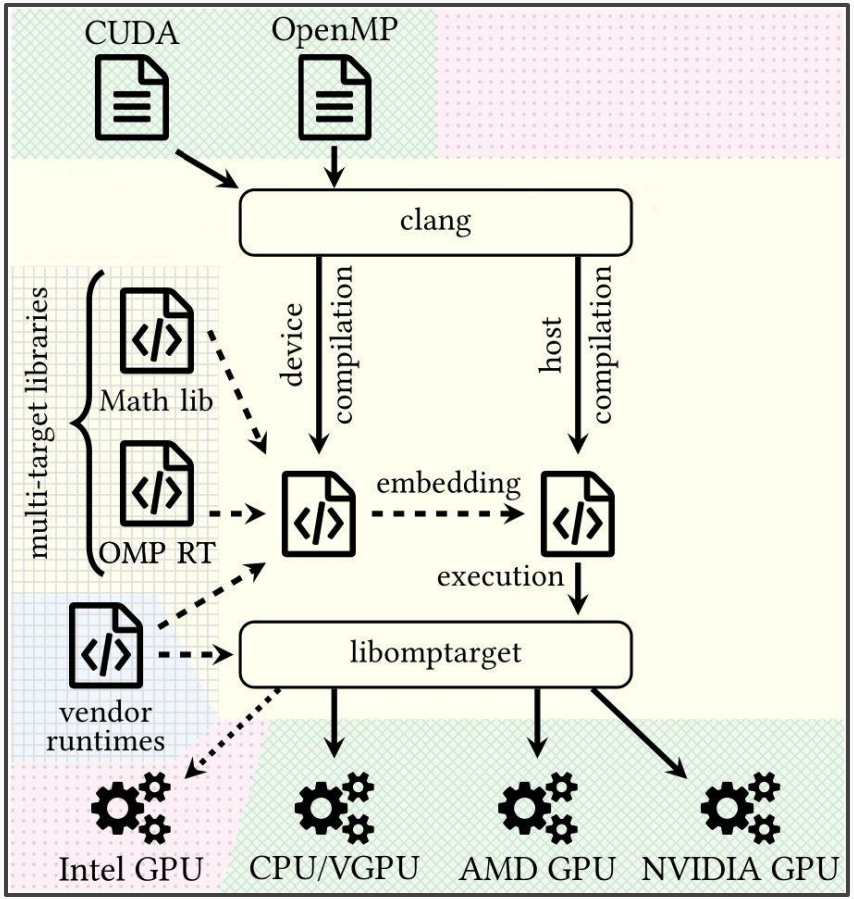

- OpenMP offload code compilation for CPUs, virtual GPU (VGPU), AMD and NVIDIA GPUs
- Intel GPU support is WIP

# LLVM/OpenMP Target Offloading + Math Runtimes




- OpenMP offload code compilation for CPUs, virtual GPU (VGPU), AMD and NVIDIA GPUs
- Intel GPU support is WIP
- Target independent math library (libm.a) for all supported architectures. Defines `sin(...), etc.`

# LLVM/OpenMP Target Offloading + CUDA Device Compilation

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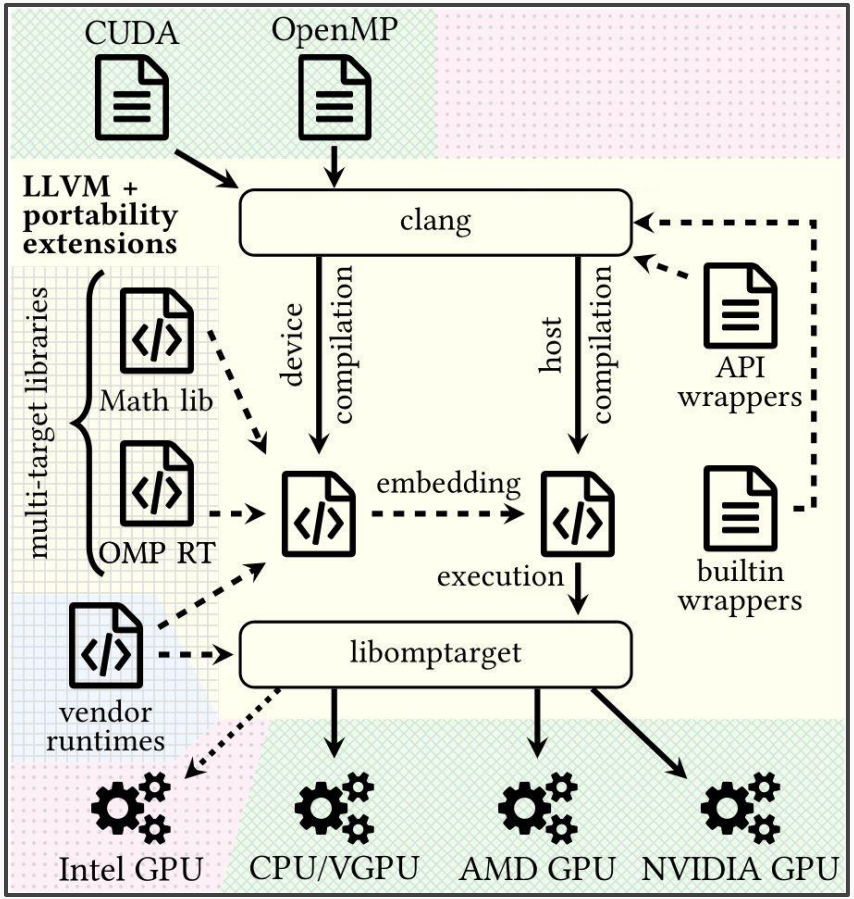
- Target independent math library (libm.a) for all supported architectures. Defines `sin(...)`, etc.
- CUDA device code interoperability with OpenMP target. Link in CUDA device runtimes e.g., Thrust.

# LLVM/OpenMP as Target Independent Runtime Layer (for CUDA)

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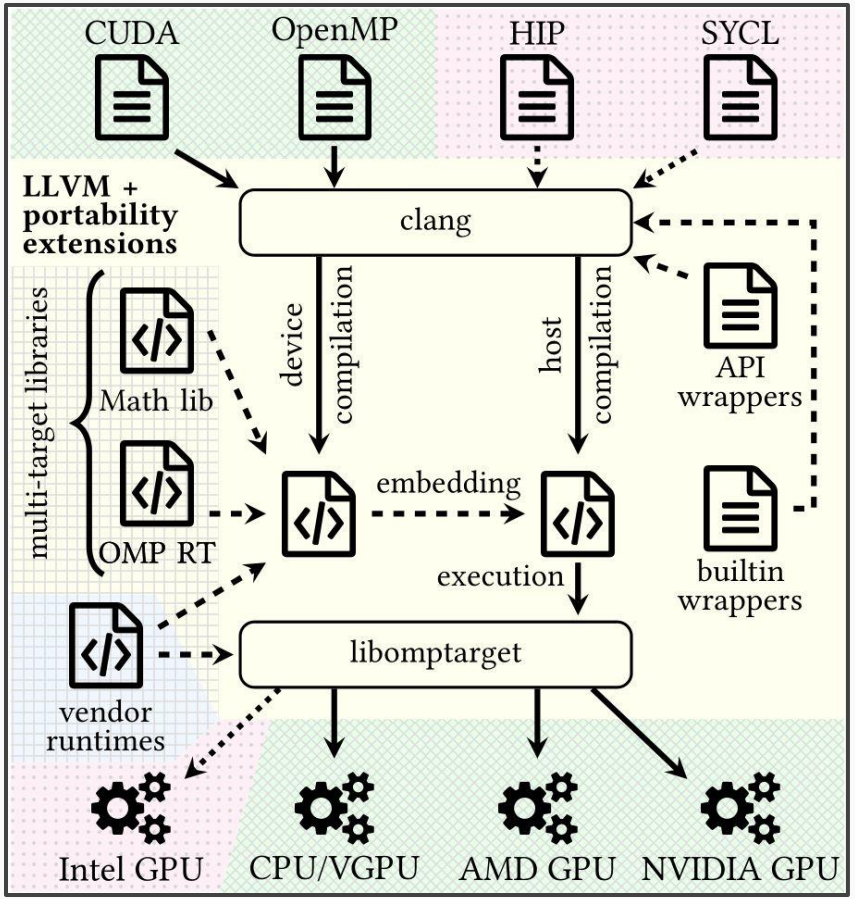
- Target independent math library (libm.a) for all supported architectures. Defines `sin(...)`, etc.
- CUDA device code interoperability with OpenMP target. Link in CUDA device runtimes e.g., Thrust.
- Define CUDA API and builtins through OpenMP runtime functions. Allow to retarget CUDA codes.

# LLVM/OpenMP as Target Independent Runtime Layer (WIP)

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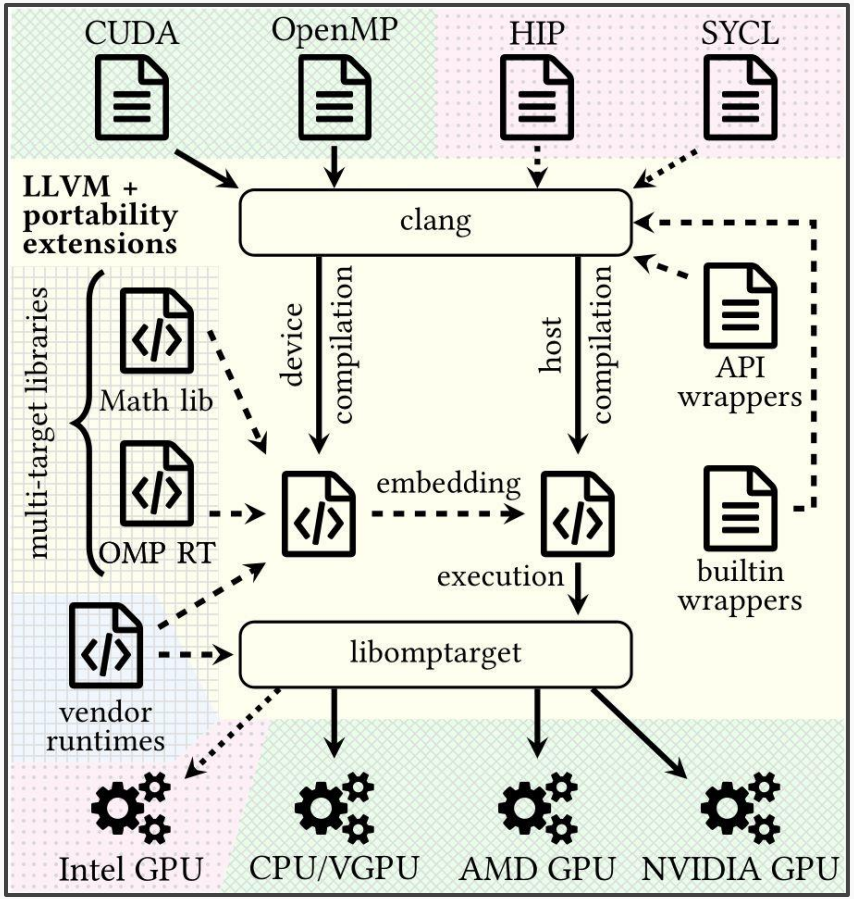
- HIP, SYCL, and other languages can be added as needed. Full interoperability and portability.

# LLVM/OpenMP as Target Independent Runtime Layer (WIP)




- OpenMP offload code compilation for CPUs, virtual GPU (VGPU), AMD and NVIDIA GPUs
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- Target independent math library (libm.a) for all supported architectures. Defines `sin(...)`, etc.
- CUDA device code interoperability with OpenMP target. Link in CUDA device runtimes e.g., Thrust.
- Define CUDA API and builtins through OpenMP runtime functions. Allow to retarget CUDA codes.
- HIP, SYCL, and other languages can be added as needed. Full interoperability and portability.
- Overall WIP but proof-of-concept is ready and under review (PACT) right now. Parts have been upstreamed (incl. Driver) or are prepared to be.

# LLVM/OpenMP as Target Independent Runtime Layer (WIP)

```
Thread 17 "su3" hit Breakpoint 1, k_mat_nn (a=0x[...]8b10, b=0x[...]
      cb20, c=0x[...]cc50, total_sites=256) at ./mat_nn_cuda.hpp:22
22 int myThread = blockDim.x * blockIdx.x + threadIdx.x;
(gdb) bt
#0 k_mat_nn (a=0x[...]8b10, b=0x[...]cb20, c=0x[...]cc50,
      total_sites=256) at ./mat_nn_cuda.hpp:22
#1 0x[...]d6dd in ?? () from /usr/lib64/libffi.so.7
#2 0x[...]9a69 in VGPUTy::VGPUTy()::{lambda()#2}::operator()() ()
   from [...]/lib/libomptarget.rtl.vgpu.so
(gdb) print myThread
$2 = 15
(gdb) next
25 if (mySite < total_sites) {
(gdb) cont
Continuing.

Thread 17 "su3" hit Breakpoint 2, k_mat_nn (a=<opt out>, b=<opt out>,
       c=0x[...]cc50, total_sites=256) at ./mat_nn_cuda.hpp:32
32 CMULSUM(a[mySite].link[j].e[k][m], b[j].e[m][l], cc);
(gdb) next
36 c[mySite].link[j].e[k][l] = cc;
(gdb) print cc
$3 = {real = 1, imag = 0}
```

Host GDB running the SU3 bench CUDA code via the OpenMP layer on the virtual GPU.

# LLVM/OpenMP as Target Independent Runtime Layer (WIP)

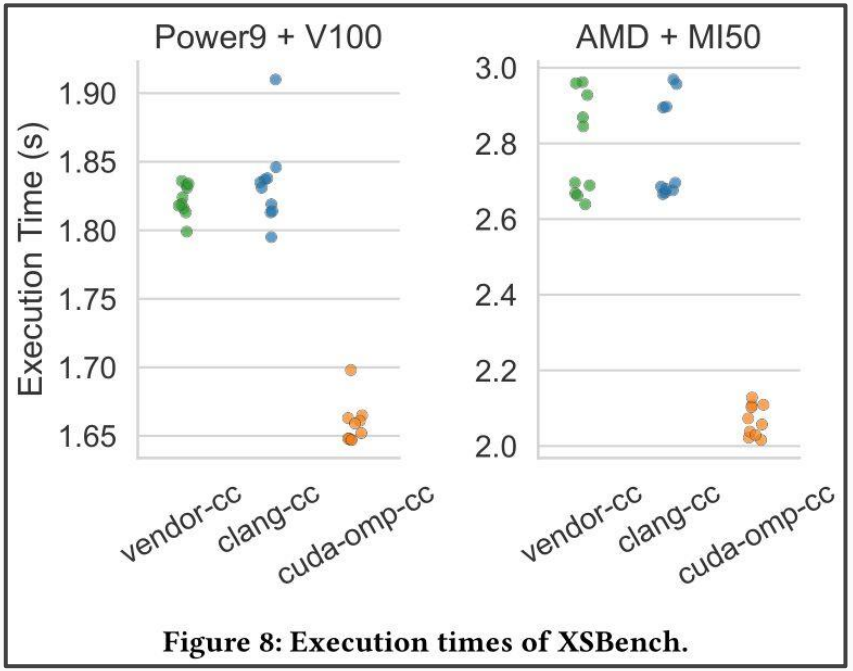



**Figure 8: Execution times of XSBench.**

Breaking the Vendor Lock — Performance Portable Programming Through OpenMP as Target Independent Runtime Layer (PACT'22, accepted)

# LLVM/OpenMP as Target Independent Runtime Layer (WIP)

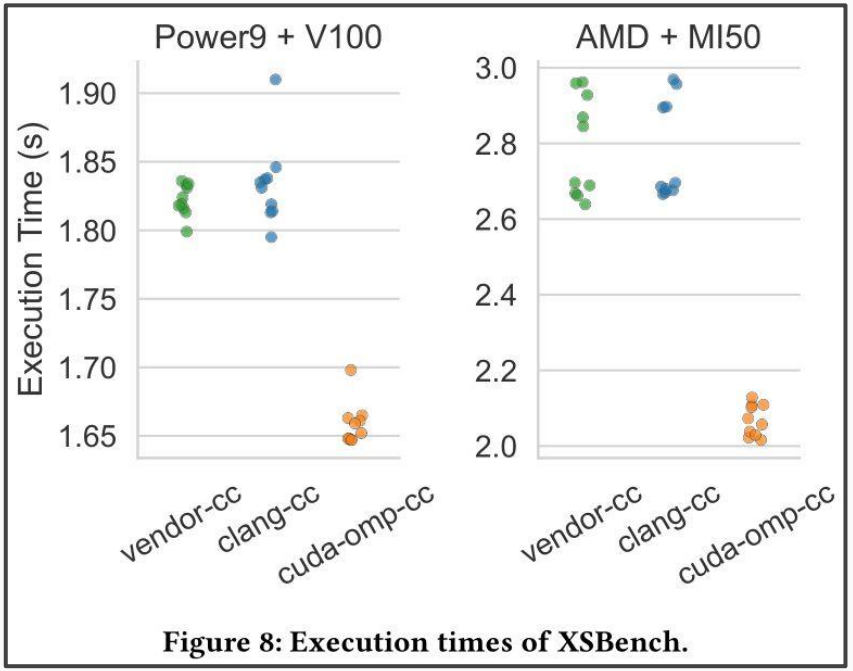



**Figure 8: Execution times of XSBench.**

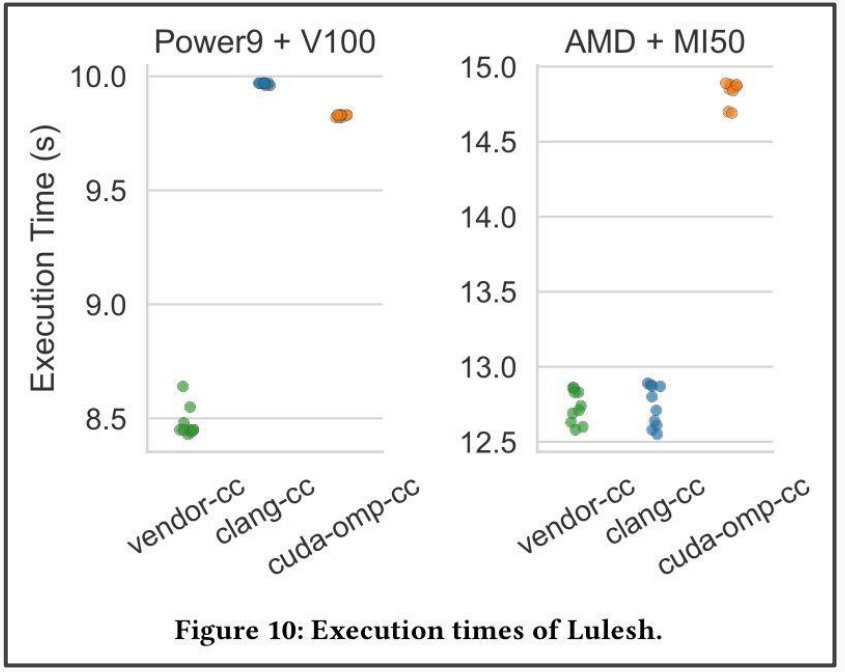
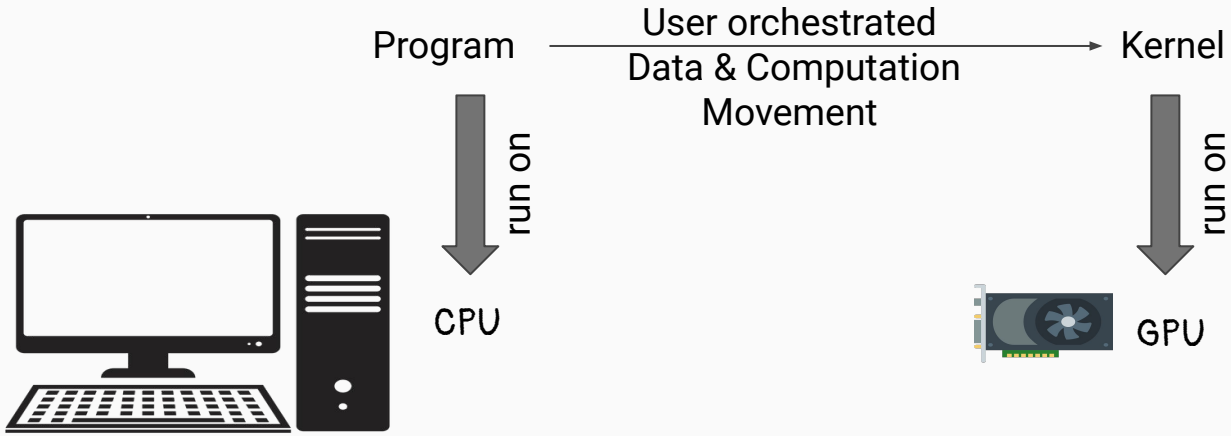



**Figure 10: Execution times of Lulesh.**

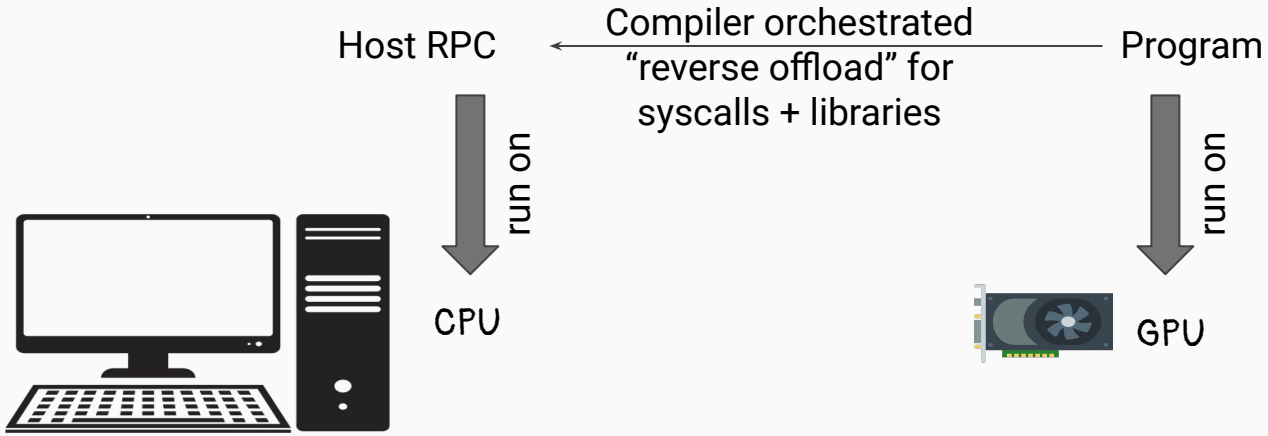
Breaking the Vendor Lock — Performance Portable Programming Through OpenMP as Target Independent Runtime Layer (PACT'22, accepted)

# Direct GPU Compilation

# Direct GPU offloading



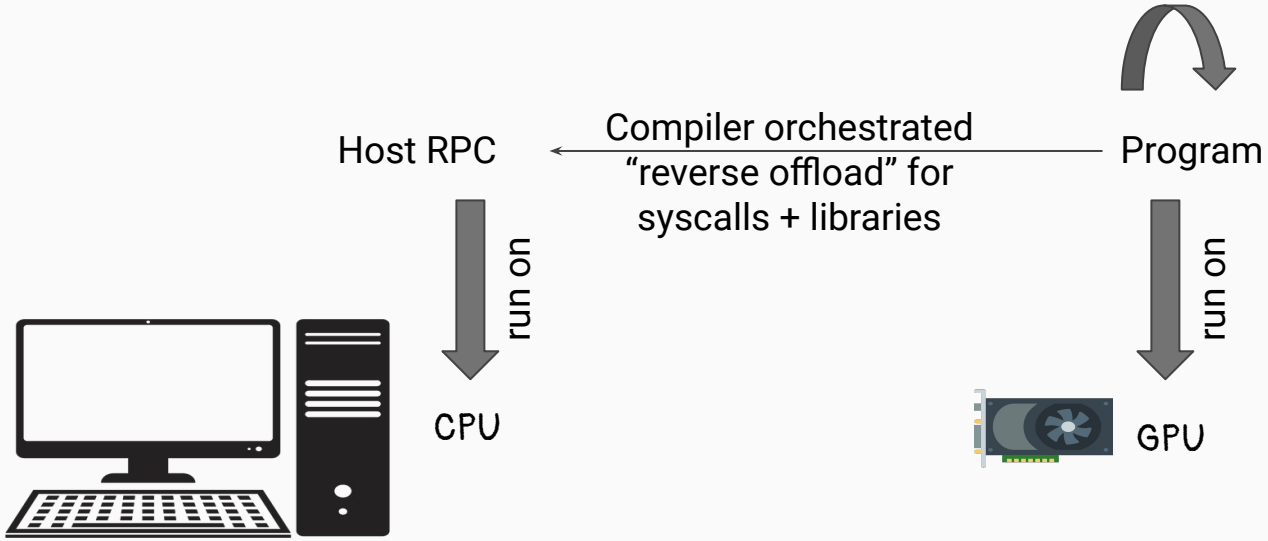
# Direct GPU offloading

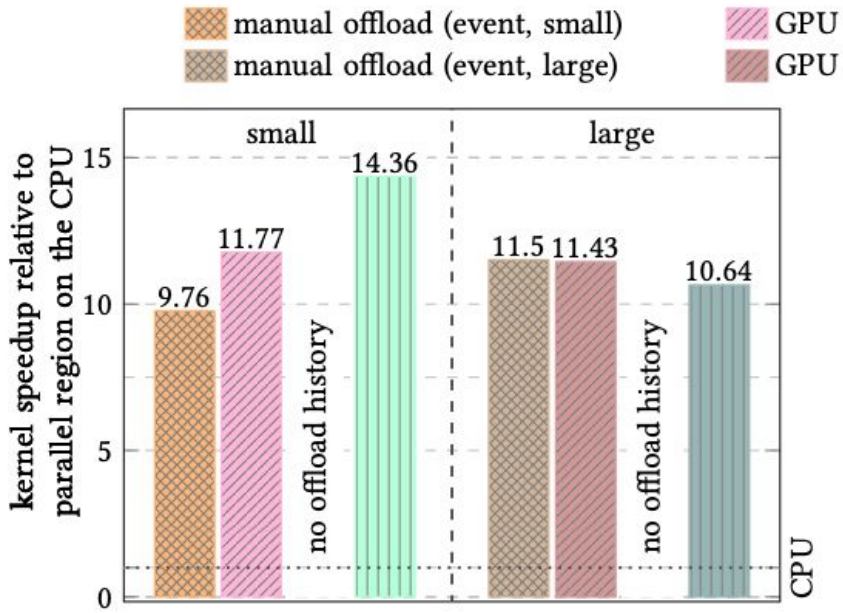



Direct GPU Compilation and Execution for Host Applications with OpenMP Parallelism (LLVM-HPC’22, accepted)

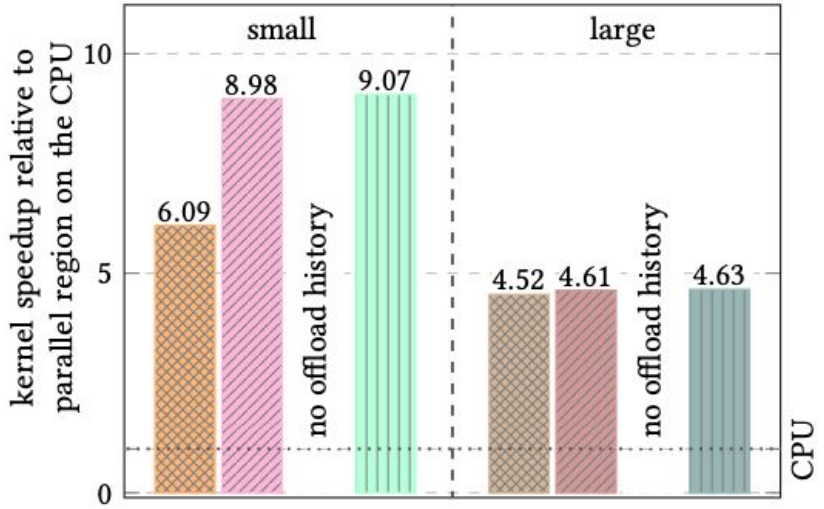
# Direct GPU offloading

```
#omp parallel for ⟶
#omp target teams distribute parallel for
```






(a) Performance of the compute kernel of XSBench relative to the CPU version.




(b) Performance of the compute kernel of RSBench relative to the CPU version.

**Figure 8: Performance of different GPU versions of the OpenMC proxy applications XSBench and RSBench compared to their respective CPU counterpart.**