Evolving “convergent”: Lessons from Control Flow in AMDGPU

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Context

- IR: Add convergence control operand bundle and intrinsics
  - https://reviews.llvm.org/D85603
- New control flow implementation in the AMDGPU backend
  - https://github.com/nhaehnle/llvm-project/tree/controlflow-wip-v7
History of ‘convergent’

barrier()

“Wait for all other threads in the threadgroup to reach the same point in the program”
bool cond = ...;
for (int i = 0; i < 4; ++i) {
    if (cond) {
        A(i)
    } else {
        B(i)
    }
    barrier();
}

bool cond = ...;
if (cond) {
    for (int i = 0; i < 4; ++i) {
        A(i)
    }
    barrier();
} else {
    for (int i = 0; i < 4; ++i) {
        B(i)
    }
    barrier();
}
Barriers and loop unrolling

```cpp
bool cond = …;
for (int i = 0; i < 4; ++i) {
    if (cond) {
        A(i)
    } else {
        B(i)
    }
    barrier();
}
```
Current definition of ‘convergent’

From LangRef:

When [convergent] appears on a function, it indicates that calls to this function should not be made control-dependent on additional values.
Convergent JumpThreading has issues

```
if (flag)
  flag = ...

if (condition)
  flag = ...
  if (flag)
    barrier()

...  ...
```

![Diagram of the code flow](Image)
SIMT execution: threads mapped onto lanes of SIMD hardware

- LLVM IR should not care about linear temporal orderings
- LLVM IR must care about whether threads are converged or not
Why LLVM cares: Cross-lane operations

```c
bool cond = ...;
int value = ...;
if (cond) {
    value = foo();
} else {
    value = bar();
}
int sum = subgroupAdd(value);
```

- subgroupAdd computes sum over all “active” threads that are mapped to the same vector
  - Communication with other threads
  - Key question: How is the set of communicating threads defined?
void fn_continue() {
    // (A)
    do {
        // (B)
        if (...) continue;
        // (C)
    } while (...);
    // (D)
}
Unstructured loops allow many convergence behaviors

```c
void fn_loopnest() {
    // (A)
    do {
        do {
            // (B)
        } while (...);
        // (C)
    } while (...);
    // (D)
}
```

- Same CFG, different expected convergence behavior based on high-level language source
- Loss of information: CFG by itself doesn’t bound convergence behavior at all
void fn_break() {
    // (A)
    for (;;) {
        // (B)
        if (...) {
            // (C)
            break;
        }
    }
    // (D)
}

- With convergent operations in (C), maximal reconvergence may not be desired
Composition

- Functions that internally use convergent operations may or may not “care about” the “active set of threads” with which they are called
  - For subgroupAverage, the set of communicating threads is part of the contract with the caller
  - unorderedAppend only requires that all convergent operations communicate among the same set of threads
- Want a way to express this distinction in IR

```c
float subgroupAverage(float x) {
    return subgroupAdd(x) / subgroupAdd(1);
}

void unorderedAppend(T data) {
    uint popcount = subgroupAdd(1);
    uint base;
    if (subgroupElect())
        base = atomicAdd(bufferTail, popcount);
    uint idx = subgroupBroadcastFirst(base) + subgroupExclusiveAdd(1);
    buffer[idx] = data;
}
```
Convergent: a new definition

- Convergent operations communicate with other threads
- The set of communicating threads is the set of threads that executes the same dynamic instance

Basic rules:
- Different static instructions $\rightarrow$ different dynamic instances
- Different executions of the same static instruction by the same thread (e.g. different loop iterations) $\rightarrow$ different dynamic instances
- Different threads executing the same static instruction $\rightarrow$ may be the same dynamic instance

- Only the dynamic instances of convergent operations are relevant for program behavior
Spontaneous divergence and reconvergence is generally allowed

- Additional tools are required to usefully constrain dynamic instances
Convergence control bundles and intrinsics

**Intrinsics producing convergence control token values**

- `token @llvm.experimental.convergence.entry()` convergent readnone
- `token @llvm.experimental.convergence.loop()` [ "convergencectrl"(token) ] convergent readnone
- `token @llvm.experimental.convergence.anchor()` convergent readnone

**Convergent operations are controlled**

- `call void @myConvergentOperation()` [ "convergencectrl"(token %tok) ]

**Fundamental rule:**
- Let $U$ be a controlled convergent operation [...] whose convergence token is produced by an instruction $D$
- Two threads executing $U$ execute the same dynamic instance of $U$ if and only if they obtained the token value from the same dynamic instance of $D$
Enforcing reconvergence: the simplest case

Control-flow graph

Reconvergence

No reconvergence
Enforcing reconvergence: a partial case

Control-flow graph

Tight reconvergence

Late reconvergence
Enforcing non-reconvergence: break blocks

```c
void fn_break() {
  // (A)
  for (; ;) {
    // (B)
    if (...) {
      // (C)
      break;
    }
  }
  // (D)
}
```
Difference between “entry” and “anchor”

- **Entry** links to the set of threads in the caller
  - Dynamic instances of “entry” congruent to dynamic instances of “call” instruction
  - Can only appear in a function’s entry block
  - Use in subgroupAverage

- **Anchor** can appear anywhere, provides no guarantees
  - Dynamic instances are implementation-defined
  - Intention is to capture as many threads as possible while allowing maximum freedom for optimizations
  - Use in unorderedAppend
- Contradicts the fundamental rule of controlled convergent operations!
- This is defined to be invalid IR (addition to the IR verifier will flag this)
Loop hearts

- Loop heart rule: two threads execute the same dynamic instance of a loop heart if and only if the convergence token was produced by the same dynamic instance and both threads execute the heart the n’th time with that value (same n)
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Impact of the new “convergent” on the compiler flow

- **Frontend**
  - Insert “convergencectrl” bundles and instructions for languages with convergent operations
  - Clang?
  - Done

- **Transforms**
  - Transforms
  - Generic transforms are conservatively correct if they “don’t move convergent operations across control flow”
  - Done
  - No general theorem, but that’s what experience suggests so far
  - No known cases of spooky action at a distance

- **Backend**
  - WIP
  - Ensure convergence as required by convergence control intrinsics
  - Backend

- **Uniform / Divergence analysis**
  - Bug fixing
  - Uniformity of values can be affected by convergence control intrinsics
  - A value V is uniform at a program point P if an appropriately controlled convergent operation in P sees the same value of V in all communicating threads
  - To do
  - Want an API where users of divergence analysis can query the correct convergence control intrinsics / token to be inserted
The end

- History of “convergent”
- Cross-lane operations and examples
- Composition
- Convergence control intrinsics and rules for dynamic instances

https://reviews.llvm.org/D85603

token @llvm.experimental.convergence.entry() convergent readnone
token @llvm.experimental.convergence.loop() [ "convergencectl"(token) ] convergent readnone
token @llvm.experimental.convergence.anchor() convergent readnone

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