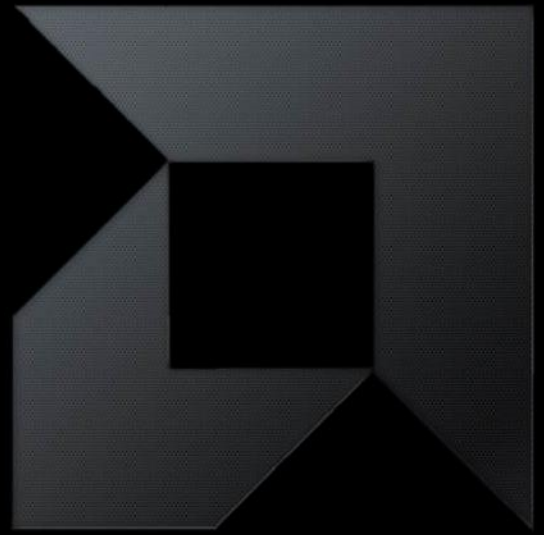
TASKS, FUTURES AND ASYNCHRONOUS PROGRAMMING



AMD

TASK-PARALLELISM

- OpenCL, CUDA, OpenMP (traditionally) and the like are largely data-parallel models
  - Their core unit of parallelism is a data element
  - Parallel dispatches are spread across that data
  - Generally the operation to be performed is closely related if not identical

- Task parallelism is a little more general
  - The tasks may or may not operate on directly-related data
  - Of course, data-parallel executions are, inherently, task parallel at some level

TASKS

- Tasks can be seen as self contained units of execution
  - Usually viewed as scalar and hence distinct from data-parallel executions

- In reality a data-parallel dispatch such as those in OpenCL can be viewed as:
  - a task
  - a tree of tasks
  - a parallel launch of tasks

- It’s all in the way it is interfaced!

- An OpenCL launch is probably best viewed as a single data-parallel task
  - Synchronization and scheduling is at kernel launch granularity.

TASK PARALLEL RUNTIMES

- Designed to efficiently execute tasks as basic units of work
  - Usually implemented on top of some sort of thread pool

- Provide a set of basic functionality:
  - synchronization primitives
  - memory sharing constructs
  - data containers and parallel algorithms

- Work on the basic of queues of tasks
  - Load balancing achieved by work stealing or work donation

MICROSOFT CONCURRENCY RUNTIME (CONCRT)

- A high level concurrency runtime distributed with the visual studio development suite
- Combines with the parallel primitives library to provide a set of useful functionality
- Cooperatively scheduled
  - At the task scheduler level
  - Of course the OS will still preemptively switch the ConcRT threads
  - Uses a work stealing scheduler to balance work
- Uses the latest features of the C++ programming language

WHAT FEATURES? (THIS WILL BE IMPORTANT LATER…)

- C++ really is simplifying the experience for the programmer
  - ConcRT's API is significantly cleaner than earlier task-parallel runtimes as a result

- Some of the earliest adopted C++11 features in compilers are being adopted for this reason:
  - Lambda
  - auto
  - r-value references

ADDITIONS TO THE C++ PROGRAMMING LANGUAGE: LAMBDA FUNCTIONS

- Lambda expressions represent a simplified syntax for constructing closures
  - Code constructs that can be passed around, encapsulating their data requirements

- We could do this in C++ already with function objects
  - Function object syntax is high overhead
  - Short functions are clumsy to write

- Lambdas simplify this

THE PATH TO LAMBDAS

- A function object that multiples an element by a construction-defined constant:

```
struct FunctionObject {
  int m_;
  FunctionObject(int m) : m_(m){}
  int operator()(int a) {
    return a*m_;
  }
}
```

- This could be passed to some sort of parallel for function to square an array:

```
parallel_for_each( vectorIn, vectorOut, FunctionObject(2) );
```

IMPROVING USING LAMBDAS

- The same operation can be achieved using the new lamda syntax more succinctly:

```
int m = 2;
parallel_for( vectorIn, vectorOut, [=](int a){return a*m;} );
```

- Of course that assignment of m was slightly contrived
  - Clearly similar benefits can be achieved on more realistic code

- The lambda syntax may be directly translated by the compiler into something resembling the function object we saw earlier
  - “captured” variables convert to construction-defined fields (by value or reference)
  - Lambda parameters represent the parameters of the () operator overload

- Return type can be inferred in simple cases, or specified using the new post-definition of return type:

```
[=](int a){return a*m;} -> int
```

ADDITIONS TO THE C++ PROGRAMMING LANGUAGE: R-VALUE REFERENCES

- A new type of reference in C++
  - Represented by &&
  - “The best things ever” – Ben Gaster (I’ll let his wife know he said that…)

- Allow the programmer to represent r-values as being different from l-values
  - l-values and r-values follow different rules
  - An l-value persists beyond the defining expression
  - Compilers can optimize r-values more heavily
  - Previously hard to distinguish the two, leading to complicated analysis of code and reduced compositionality

R-VALUE REFERENCES

- Allow the programmer to change behavior based on the type of reference
  - For example, the process of moving data from one vector to another is different from the process of copying

```
class vector {
    vector operator=(vector &rhs) {
        if( size_ != rhs.size_ )
            // resize data_
        memcpy(data_, rhs.data_, size_);
    }
    vector operator=(vector &&rhs) {
        size_ = rhs.size_;
        data_ = rhs.data_;
    }
}
```

Traditional reference assignment needing deep copy

Move assignment where only copying the pointer and size is necessary

BENEFITS TO THE COMPILER AND DEVELOPER

- Note that the information is now encoded in the type system
- The compiler can select the appropriate function to use based on the type
  - And propagate that information through call graphs
- Helps when return value optimization is difficult to achieve
- This reduces the overhead when we are passing C++ objects around and simplifies the set of constructors and assignment operators we need to create
  - More pleasant experience for the programmer!

ADDITIONS TO THE C++ PROGRAMMING LANGUAGE: AUTO AND DECLTYPE

- C++ is a statically typed language and is famously verbose:
  - std::vector<std::vector<int>> *a = new std::vector<std::vector<int>>(10);
- Looking at that we might wonder why the type of a is necessary at all, it can be inferred can't it?
- C++11 repurposes the `auto` keyword (previously this was a storage qualifier similar to `register`)
  - auto a = new std::vector<std::vector<int>>(10);
- Of course with `using namespace` we can decrease it further

DECLTYPE

- Decltype allows us to request the type of an entity for use

- Let's say we want to construct a lambda that takes a version of the current object as a parameter, we might do:
  - `auto l = [](decltype(this) t){ t->doSomething(); return new decltype(this)(*t); } -> decltype(this);`

- So we:
  - Take a pointer to the current type
  - Apply a function to it
  - Return a copy
  - Specify the type returned using the new return type post-declaration operator

MAKING CONCURRENT PROGRAMMING CLEANER USING C++11 FEATURES

- Introducing this to give some idea how C++11 features can be used in a CPU runtime

- Use some of the early C++11 features
  - Lambdas to make easy task construction
  - auto and decltype to streamline typing

- Cooperative threading:
  - Tasks yield to other tasks and completely occupy the worker thread while running

- Note that TBB 4 has many similar features

SIMPLEST CASE TASKING IN CONCRT IS VERY SIMPLE

- Uses the Concurrency namespace
- Create a task from a function object:
  - `auto concRTTask = Concurrency::make_task([] { std::cout<<"Something printed\n"; })`
- Create a task group that manages task execution:
  - `Concurrency::task_group taskPool;`
- The task group schedules tasks onto the thread pool.
- Tasks can dispatch other tasks and wait on the results – the wait is a cooperative threading construct that pushes the task out of the system.
- Run the task in the pool and wait on its completion:
  - `taskPool.run( concRTTask );`
  - `taskPool.wait();`

PARALLEL ALGORITHMS

- parallel_for
  - Repeatedly performs the same task in parallel
  - Parameterises with an iteration value

```
parallel_for(1, 6,
  [](int value) { wstringstream ss; ss << value << L' '; wcout << ss.str(); });
```

- parallel_for_each
  - Parameterises with a value from a container such as a vector or array

```
parallel_for_each(values.begin(), values.end(),
  [](ValueType value) { wstringstream ss; ss << value << L' '; wcout << ss.str(); });
```

- parallel_invoke
  - Executes a set of tasks in parallel and returns only on completion of the entire set

```
parallel_invoke( [&n] { n = twice(n); },
  [&d] { d = twice(d); }, [&s] { s = twice(s); } );
```

PARALLEL CONTAINERS

- Concurrency safe append and read/dequeue operations:
  - `concurrent_vector`
  - `concurrent_queue`

- Combinable class
  - Offers thread-local storage that is combined into a final result
  - Provides reduction functionality

A COUPLE OF EXTENSIONS

- Let’s add a couple of constructs that will help us later
  - The PPL extras in the sample pack contain related ideas if you’re interested in implementations

- PPL tasks rely on task-groups for waiting. What if instead we could wait on the returned value?
  - Futures are representations of types with asynchronously generated values
  - Data is promised to a future by an executing task, often as the return value

FUTURES

- Conceptually:

```
Task t = make_task(functionThatReturnsAnInt);
Future<int> a = t.run();
…
int b = a.get();
```

- That is that if we have some way to asynchronously launch a unit of work, we might wrap its return type so that we can execute in parallel
  - We only synchronize when we need the return value

CONTINUATIONS

- Another useful construct for concurrent programming

- Continuations are units of code (tasks) that are enqueued to execute after something else:

```
Task a = make_task(……);
Task b = make_task(……);
a.continueWith(b);
Future fA = a.enqueue();
```

- Of course, there is a limitation of writing it this way:
  - How do we cleanly get the future resulting from b?

NESTED ENQUEUE

- The following might be one approach

```
Future FunctionA(Task t) {
  // Body of a
  …
  // Task A enqueues its continuation internally, and returns (no wait)
  return t.enqueue();
}
Task a = make_task(……);
Task b = make_task(……);
Future fA = a.enqueue(b); // A takes a parameter of its continuation
Future fB = fA.get();     // The return value from A was a future
int b = fB.get();
```

- Of course, there is a limitation of writing it this way:
  - How do we cleanly get the future resulting from b?

LIMITATIONS OF CONCRT AND THE PPL

- PPL tasks are grouped, but are not inherently data-parallel

- Data-parallel constructs in the PPL are executed as task trees
  - Such structures are not directly suitable for GPU execution
  - We will show some enhancements…

- The continuation and future mechanisms can be encoded on ConcRT tasks
  - They need to be first-class if we want to execute such constructs on heterogeneous systems
  - They can still be **implemented** the ConcRT way on the CPU

- Ben will later explain how we can apply some of these ideas, but first he'll talk about the current state-of-the-art

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