OpenCL 2.0, OpenCL SYCL & OpenMP 4

Open Standards for Heterogeneous Parallel Computing

Ronan Keryell

AMD
Performance & Application Engineering
Sunnyvale, California, USA

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High Performance Computing & Supercomputing Group of Paris

Present and future: heterogeneous...

- Physical limits of current integration technology
  - Smaller transistors
  - More and more transistors ☺
  - More leaky: static consumption ☹
  - Huge surface dissipation ☹
    - Impossible to power all the transistors all the time ⇝ "*dark silicon*"
    - ⇝ Specialize transistors for different tasks
    - Use hierarchy of processors ("big-little"...)
    - Use myriads of specialized accelerators (DSP, ISP, GPU, cryptoprocessors, IO...)
- Moving data across chips and inside chips is more power consuming than computing
  - Memory hierarchies, NUMA (Non-Uniform Memory Access)
  - Develop new algorithms with different trade-off between data motion and computation
- Need new programming models & applications
  - Control computation, accelerators, data location and choreography
  - Rewrite most power inefficient parts of the application ☹

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Outline

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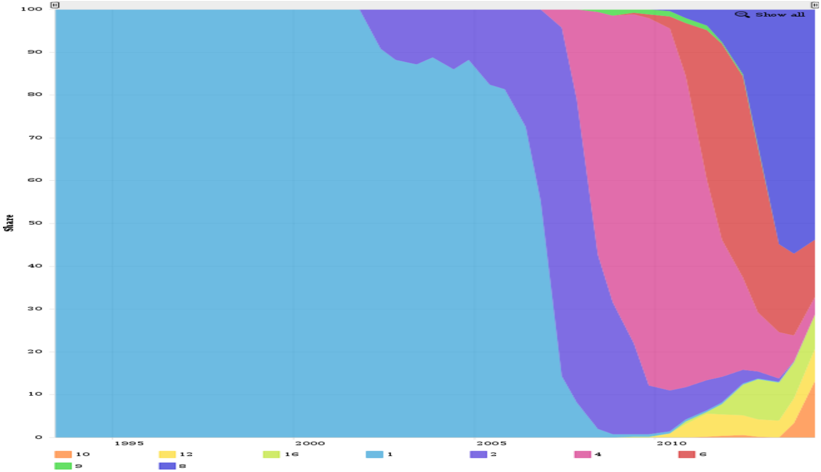
Top 500 on 2014/06

LINPACK (LU factorization) `http://www.netlib.org/benchmark/hpl`

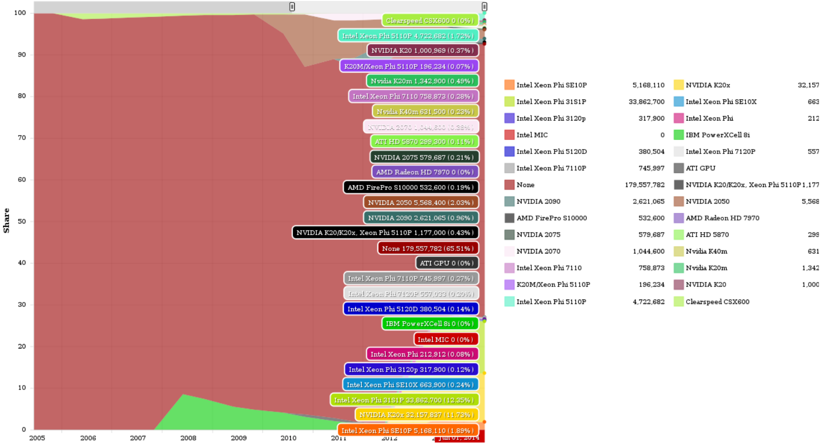
Rank	Site	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	National Super Computer Center in Guangzhou China	**Tianhe-2 (MilkyWay-2)** - TH-IVB-FEP Cluster, Intel Xeon E5-2692 12C 2.200GHz, TH Express-2, Intel Xeon Phi 31S1P NUDT	3,120,000	33,862.7	54,902.4	17,808
2	DOE/SC/Oak Ridge National Laboratory United States	**Titan** - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x Cray Inc.	560,640	17,590.0	27,112.5	8,209
3	DOE/NNSA/LLNL United States	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom IBM	1,572,864	17,173.2	20,132.7	7,890
4	RIKEN Advanced Institute for Computational Science (AICS) Japan	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect Fujitsu	705,024	10,510.0	11,280.4	12,660
5	DOE/SC/Argonne National Laboratory United States	**Mira** - BlueGene/Q, Power BQC 16C 1.60GHz, Custom IBM	786,432	8,586.6	10,066.3	3,945
6	Swiss National Supercomputing Centre (CSCS) Switzerland	**Piz Daint** - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x Cray Inc.	115,984	6,271.0	7,788.9	2,325

Top 500 cores per socket systems share



Top 500 performance share of accelerators

`http://top500.org/statistics/overtime`



Green500 List (June 2014)

http://www.green500.org

- Top 1: TSUBAME-KFC: 4.39 GFLOPS/W
- First 15 systems: NVIDIA Kepler K20 GPUs + Intel Xeon CPUs
  - Top 6: ROMEO HPC Center — **Champagne!**-Ardenne ☺ from Bull
- Number 16 system: Intel Xeon Phi + Intel Xeon CPUs
- Number 17 system: AMD FirePro S10000 GPUs + Intel Xeon CPUs

Electrical power dissipation is **the** problem

Approximate power consumption with 28 nm technology (data from US Exascale Echelon project)

- 64-bit DP FLOP: 20 pJ (80 pJ for 4 64-bit floats)
- Register file access: 2 pJ
- 256-bit access to on-chip 8 kB SRAM: 50 pJ
- 150 pJ for integrated cache access
- 300 pJ for external cache (?)
- 256-bit bus on 20 mm: 1 nJ
  - 30 pJ for return trip of 4 64-bit floats ≡ 0.6 mm
- External access to DRAM: 16 nJ
- Efficient off-chip link: 500 pJ (?)

Need to apply this to programming too... ☹

- Where is Java/C#/JavaScript/SQL/... in the list? ⚠ ⚠ ⚠

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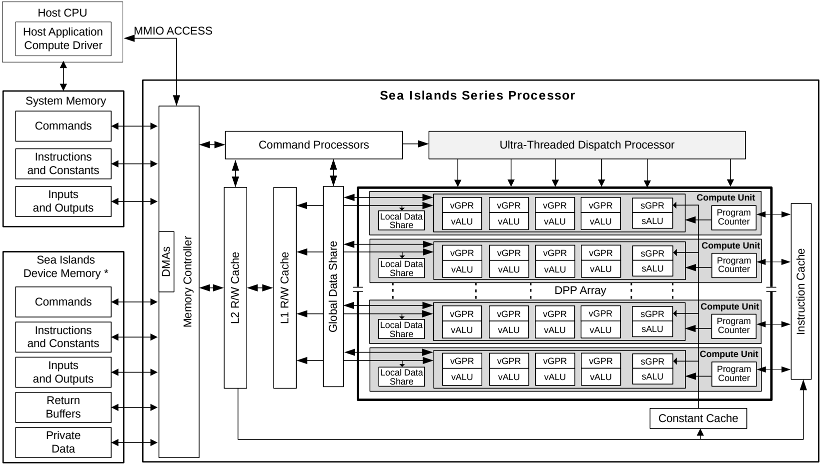
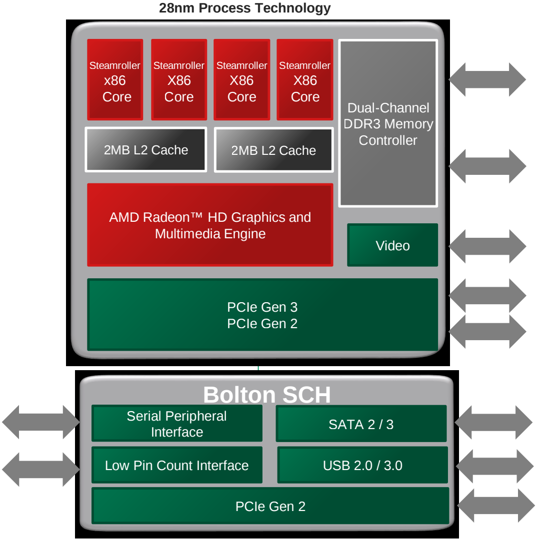
dGPU AMD FirePro W9100

6.2.10^9 transistors, 5.24 TFLOPS SP (2.62 DP), 2816 ALUs (44 compute units with 64 ALUs), 16 GB GDDR5 ECC 320 GB/s, 6 4K displays, 275 W



*Discrete GPU – Physical Device Memory; APU – Region of system for GPU direct access

APU AMD Kaveri



Qualcomm Snapdragon 801 (smart-phone...)

- CPU: 2.5 GHz quad-core Krait 400 CPU (32 bit ARM)
- GPU: Adreno 330, 578 MHz, 32 ALUs of 5-way VLIW, 166.5 GFLOPS (OpenGL ES 3, OpenCL 1.2 Embedded Profile)
- DSP Hexagon (QDSP) V50 DSP (up to 800MHz)
- DRAM LPDDR3 933MHz dual-channel 32-bit (12.8 GB/s)
- 4G LTE, WCDMA (DC-HSUPA), TD-SCDMA, GSM/EDGE...
- FM radio RDS
- USB 3.0/2.0
- Bluetooth BT4.0
- WiFi Qualcomm VIVE 1-stream 802.11n/ac
- GPS
- NFC
- Video: 4K playback and capture with H.264 (AVC), 1080p playback with H.265 (HEVC), MPEG-DASH (Adobe)
- Camera up to 21MP Dual ISP 10 bits
- Display 2560x2048 + 1080p and 4K external
- eMMC 5.0, SATA3, SD 3.0

Outline

Software (I)

- Automatic parallelization
  - Easy to start with
  - Intractable issue in general case
  - Active (difficult) research area for 40+ years
  - Work only on *well* written and simple programs ☹
  - Problem with parallel programming: current bad shape of existing sequential programs... ☹
- At least can do the easy (but cumbersome) work

Software (II)

- New parallel languages
  - Domain-Specific Language (DSL) for parallelism & HPC
  - Chapel, UPC, X10, Fortress, Erlang...
  - Vicious circle
    - Need to learn new language
    - Need rewriting applications
    - Most of // languages from last 40 years are dead
- New language acceptance ↘↘

Software (III)

- New libraries
  - Allow using new features without changing language
    - Linear algebra BLAS/Magma/ACML/PetSC/Trilinos/..., FFT...
    - MPI, MCAPI, OpenGL, OpenCL...
  - Some language facilities not available (metaprogramming...)
- Drop in approach for application-level libraries
- Full control of the performance with low-level API

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Software *(IV)*

- `#Pragma`(tic) approach
  - Start from existing language
  - Add distribution, data sharing, parallelism... hints with `#pragma`
  - OpenMP, OpenHMPP, OpenACC, XMP (back to HPF)...
- Portability

Software (V)

- New concepts in existing object-oriented language
  - Domain Specific Embedded Language (DSeL)
  - Abstract new concepts in classes
  - // STL, C++AMP, OpenCL SYCL...
- Full control of the performance

Software (VI)

- Operating system support
  - Avoid moving data around
  - Deal with NUMA memory, cache and processor affinity
  - Provide user-mode I/O & accelerator interface
  - Provide virtual memory on CPU and accelerators
  - HSA...

A good answer will need a mix of various approaches

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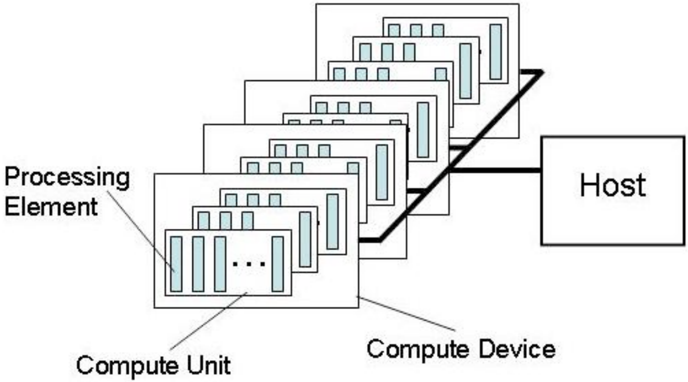
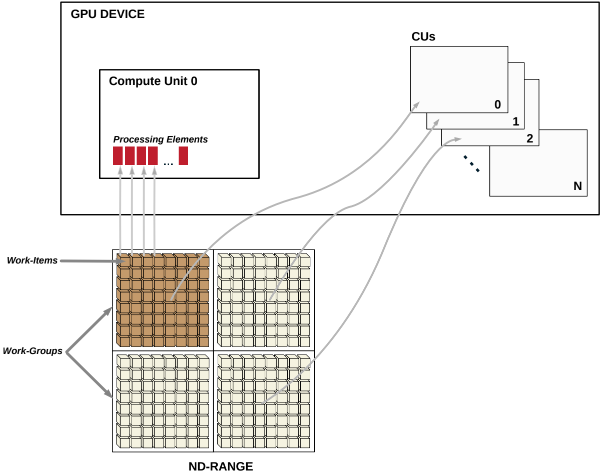
Architecture model



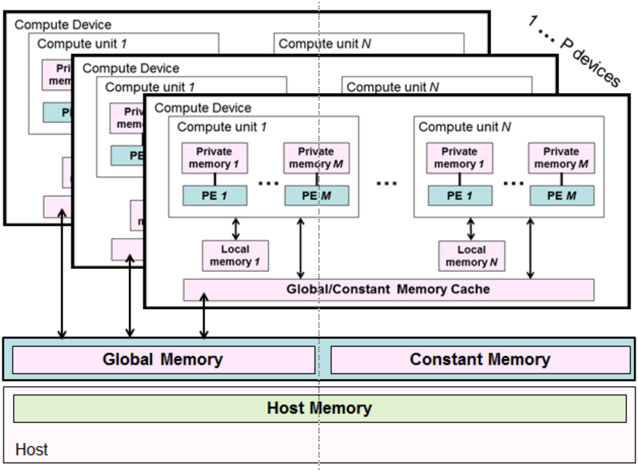
- Host threads launch computational *kernels* on *accelerators*

`https://www.khronos.org/opencl`

Execution model



Memory model



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Share Virtual Memory (SVM) *(I)*

3 variations...

Coarse-Grained memory buffer SVM

- Sharing at the granularity of regions of OpenCL buffer objects
  - `clSVMAlloc()`
  - `clSVMFree()`
- Consistency is enforced at synchronization points
- Update views with `clEnqueueSVMMap()`, `clEnqueueSVMUnmap()`, `clEnqueueMapBuffer()` and `clEnqueueUnmapMemObject()` commands
- Similar to non-SVM but allows shared pointer-based data structures

Share Virtual Memory (SVM) *(II)*

Fine-Grained memory buffer SVM

- Sharing at the granularity of individual loads/stores into bytes within OpenCL buffer memory objects
- Consistency guaranteed only at synchronization points
- Optional OpenCL atomics to provide fine-grained consistency
  - No need to use previous `...Map()/...Unmap()`

Share Virtual Memory (SVM) *(III)*

Fine-Grained system SVM *à la* C(++)11

- Sharing occurs at the granularity of individual loads/stores into bytes occurring **anywhere within the host memory**
  - Allow normal memory such as `malloc()`
- Loads and stores may be cached so consistency is guaranteed only at synchronization points
- Optional OpenCL atomics to provide fine-grained consistency

New pointer `__attribute__((nosvm))`

Lambda expressions with Block syntax

- From Mac OS X's Grand Central Dispatch, implemented in Clang

```
int multiplier = 7;
int (^myBlock)(int) = ^(int num) {
  return num*multiplier;
};
printf("%d\n", myBlock(3)); // prints 21
```

- By-reference closure but const copy for automatic variable
- Equivalent in C++11

```
auto myBlock = [=] (int num) {
  return num*multiplier;
};
```

Device-side enqueue (I)

- OpenCL 2 allows nested parallelism
- Child kernel enqueued by kernel on a device-side command queue
- Out-of-order execution
- Use events for synchronization
- ⚠ No kernel preemption ⇝ Continuation-passing style! ☺
  en.wikipedia.org/wiki/Continuation-passing_style

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Device-side enqueue (II)

```
// Find and start new jobs
kernel void
evaluate_work(...) {
  /* Check if more work needs to be performed,
     for example a tree or list traversal */
  if (check_new_work(...)) {
    /* Start workers with the right //ism on default
       queue only after the end of this launcher */
    enqueue_kernel(get_default_queue(),
                   CLK_ENQUEUE_FLAGS_WAIT_KERNEL,
                   ndrange_1D(compute_size(...)),
                   ^{ real_work(...); });
  }
}
```

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Device-side enqueue (III)

```
// Cross-recursion example for dynamic //ism
kernel void
real_work(...) {
  // The real work should be here
  [...]
  /* Queue a single instance of evaluate_work()
     to device default queue to go on recursion */
  if (get_global_id(0) == 0) {
    /* Wait for the *current* kernel execution
       before starting the *new one* */
    enqueue_kernel(get_default_queue(),
                   CLK_ENQUEUE_FLAGS_WAIT_KERNEL,
                   ndrange_1D(1),
                   ^{ evaluate_work(...); });
  }
}
```

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Collective work-group operators

- Operation involving all work-items inside a work-group
  - `int work_group_all(int predicate)`
  - `int work_group_any(int predicate)`
  - `gentype work_group_broadcast(gentype a, size_t id_x...)`
  - `gentype work_group_reduce_`*op*`(gentype x)`
  - `gentype work_group_scan_exclusive_`*op*`(gentype x)`
  - `gentype work_group_scan_inclusive_`*op*`(gentype x)`
- http://en.wikipedia.org/wiki/Prefix_sum

Subgroups

- Represent real execution of work-items inside work-groups
  - 1-dimensional
  - *wavefront* on AMD GPU, *warp* on nVidia GPU
  - There may be more than 1 subgroup/work-group...
- Coordinate `uint get_sub_group_id()`, `uint get_sub_group_local_id()`, `uint get_sub_group_size()`, `uint get_num_sub_groups()`...
- `void sub_group_barrier(...)`
- Collective operators `sub_group_reduce_op()`, `sub_group_scan_exclusive_op()`, `sub_group_scan_inclusive_op()`, `sub_group_broadcast()`...

Pipe

- Efficient connection between kernels for stream computing
- Ordered sequence of data items
- One kernel can write data into a pipe
- One kernel can read data from a pipe

```
cl_mem  clCreatePipe(cl_context context,
                     cl_mem_flags flags,
                     cl_uint pipe_packet_size,
                     cl_uint pipe_max_packets,
                     const cl_pipe_properties *props,
                     cl_int *errcode_ret)
```

- Kernel functions to read/write/test packets

ND range not multiple of work-group size

- Global iteration space may not be multiple of work-group size
- OpenCL 2 introduces concept of non-uniform work-group size
- Last work-group in each dimension may have less work-items
- Up to 8 cases in 3D
  - `size_t get_local_size (uint dimindx)`
  - `size_t get_enqueued_local_size(uint dimindx)`

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Other improvements in OpenCL 2

- MIPmaps (*multum in parvo* map): textures at different LOD (level of details)
- Local and private memory initialization (*à la* `calloc()`)
- Read/write images `__read_write`
- Interoperability with OpenGL, Direct3D...
- Images (support for 2D image from buffer, depth images and standard IEC 61996-2-1 sRGB image)
- Linker to use libraries with `clLinkProgram()`
- Generic address space `__generic`
- Program scope variables in global address space
- C11 atomics
- Clang blocks ($\approx$ C++11 lambda in C)
- `int printf(constant char * restrict format, ...)` with vector extensions
- Kernel-side events & profiling
- On-going Open Source implementations (AMD on HSA...)

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Outline

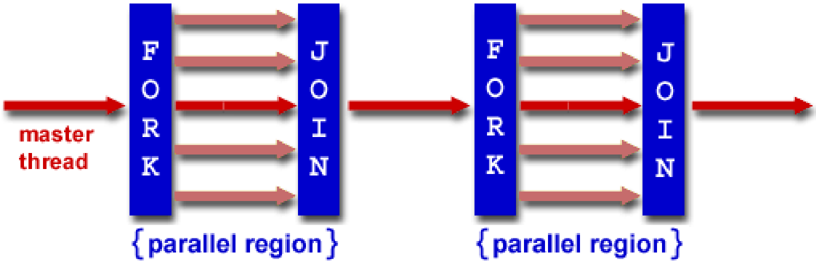
OpenMP 4

- Target (virtual) shared memory machines
- Add some directives (`#pragma...`) in existing language to help compiler
  - Parallelism
  - Data sharing with weak consistency
- ⚠ If no directive, no parallelism used (*a priori*)
- ⚠ ⚠ ⚠ Directive $\equiv$ sworn declaration
- Support C/C++/Fortran by most compilers
- Also used for other languages (Python with Pythran...)
- Unification of previous vendor `#pragma` in 1997
- OpenMP 4 (2013) supports heterogeneous accelerators!

`http://openmp.org/wp/openmp-specifications`

Thread model

- Parallel execution based on *fork/join*



- Thread creation with directive `#pragma omp parallel`
- Work distribution with `#pragma omp for`

```
#pragma omp parallel for
    for(i = 0; i < N; i++)
        neat_stuff(i);
```

Task programming (I)

```
#include <stdio.h>
int main() {
  int x = 1;
  // Start threads
#pragma omp parallel
  // Execute following block in a single thread
#pragma omp single
  {
    // Start statement in a new task
#pragma omp task shared(x) depend(out: x)
    x = 2;
    // Start statement in another task
#pragma omp task shared(x) depend(in: x)
    printf("x = %d\n", x);
  }
  return 0;
```

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Task programming (II)

```
}
```

- Can deal with normal, anti- and output dependencies

SIMD loops

- Allow vector execution in SIMD

```
#pragma omp simd
  for(int i = 0; i < N; ++i)
    x[i] = y[i] + z[i];
```

- Can limit parallelism to deal with loop-carried dependencies

```
#pragma omp simd safelen(10)
  for(int i = 10; i < N; ++i)
    x[i] = x[i - 10] + y[i];
```

SIMD version of functions

- Provide also a vector function

```
#pragma omp declare simd uniform(v) \
                linear(i) notinbranch
void init(double array[N], int i, double v) {
  array[i] = v;
}

  // [...]

  double a[N];
  double v = random123();
#pragma omp simd
  for(int i = 0; i < N; ++i)
    init(a, i, v);
```

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Loops with threads + SIMD execution

```
// Execute next block in multi-threaded way
#pragma parallel if(N > 1000)
  {
    // [...]
#pragma omp for simd
  for(int i = 0; i < N; ++i)
    x[i] = y[i] + z[i];

  } // End of the threads
```

Execution on a target device

- Possible to off-load some code to a device

```
  /* Off-load computation on accelerator
     if enough work, or keep it on host */
#pragma target if(N > 1000)
  // The loop on the device is executed in parallel
#pragma omp parallel for
  for(int i = 0; i < N; ++i)
    x[i] = y[i] + z[i];
```

- Data are moved between host and target device by OpenMP compiler

Device data environment

- Execution of distributed-memory accelerators
  - Need sending parameters
  - Need getting back results
- Allow mapping host data to target device

```
#pragma omp target data map(to: v1[N:M], v2[:M-N]) \
                        map(from: p[N:M])
  {
#pragma omp target
#pragma omp parallel for
    for (int i = N; i < M; i++)
      p[i] = v1[i] * v2[i - N];
  }
```

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Asynchronous device execution with tasks

```
#pragma omp declare target
  float F(float);
#pragma omp end declare target
#define N 1000000000
#define CHUNKSZ 1000000
  float Z[N];
void pipedF() {
  init(Z, N);
  for (int C = 0; C < N; C += CHUNKSZ)
    // Execute the following in a new task
#pragma omp task
    // Execute the following on an accelerator
#pragma omp target map(Z[C:CHUNKSZ])
#pragma omp parallel for
    for (int i = 0; i < CHUNKSZ; i++)
      Z[i] = F(Z[i]);
    // Wait for previous task executions
#pragma omp taskwait
}
```

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Execution with work-groups

```
float dotprod(int N, float B[N], float C[N],
              int block_size,
              int num_teams, int block_threads) {
  float sum = 0;
#pragma omp target map(to: B[0:N], C[0:N])
#pragma omp teams num_teams(num_teams) \
            thread_limit(block_threads) \
            reduction(+:sum)
#pragma omp distribute
  // Scheduled on the master of each team
  for (int i0 = 0; i0 < N; i0 += block_size)
#pragma omp parallel for reduction(+:sum)
    // Executed on the threads of each team
    for (int i = i0; i < min(i0+block_size, N); ++i)
      sum += B[i]*C[i];
  return sum;
}
```

Other OpenMP 4 features

- Affinity control of threads/processor
- SIMD functions
- Cancellation points
- Generalized reductions
- Taskgroups
- Atomic swap
- C/C++ array syntax for array sections in clauses
- `OMP_DISPLAY_ENV` to display current ICV values
- Open Source implementation with GCC 4.9 (on-host `target`), Clang/LLVM on-going,...

Outline

OpenCL SYCL goals

- Ease of use
- Single source programming model
  - SYCL source compiled for host and device(s)
- Development/debugging on host
- Programming interface that data management and error handling
- C++ features available for OpenCL
  - Enabling the creation of higher level programming models and C++ templated libraries based on OpenCL
- Portability across platforms and compilers
- Providing the full OpenCL feature set and seamless integration with existing OpenCL code
- High performance

Puns explained for French speakers

- OpenCL SPIR (spear: *lance, pointe*)
- OpenCL SYCL (sickle: *faucille*)

Complete example of matrix addition (I)

```
#include <CL/sycl.hpp>
#include <iostream>

using namespace cl::sycl;

constexpr size_t N = 2;
constexpr size_t M = 3;
using Matrix = float[N][M];

int main() {
  Matrix a = { { 1, 2, 3 }, { 4, 5, 6 } };
  Matrix b = { { 2, 3, 4 }, { 5, 6, 7 } };

  Matrix c;
```

Complete example of matrix addition (II)

```
{// Create a queue to work on
  queue myQueue;
  buffer<float, 2> A { a, range<2> { N, M } };
  buffer<float, 2> B { b, range<2> { N, M } };
  buffer<float, 2> C { c, range<2> { N, M } };
  command_group (myQueue, [&] () {
    auto ka = A.get_access<access::read>();
    auto kb = B.get_access<access::read>();
    auto kc = C.get_access<access::write>();
    parallel_for(range<2> { N, M },
        kernel_lambda<class mat_add>([=](id<2> i) {
      kc[i] = ka[i] + kb[i];
    }));
  }); // End of our commands for this queue
} // End scope, so wait for the queue to complete
```

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Complete example of matrix addition *(III)*

```
   return 0;
}
```

Hierarchical parallelism (I)

```
const int size = 10;
int data[size];
const int gsize = 2;
buffer<int> my_buffer { data, size };
```

Hierarchical parallelism *(II)*

```
command_group(my_queue, [&]() {
 auto in = my_buffer.get_access<access::read>();
 auto out = my_buffer.get_access<access::write>();
 parallel_for_workgroup(nd_range<>(range<>(size),
                                  range<>(gsize)),
  kernel_lambda<class hierarchical>
             ([=](group<> grp) {
    std::cerr << "Gid=" << grp.get(0) << std::endl;
    parallel_for_workitem(grp, [=](item<1> tile) {
      std::cerr << "id␣=" << tile.get_local().get(0)
                << "␣" << tile.get_global()[0]
                << std::endl;
      out[tile] = in[tile] * 2;
    });
  }));
});
```

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Some C++ functional programming

- Image processing stream
  - Apply f on image with a kernel application function
  - Apply g on previous output with a kernel application function
  - Apply h on previous output with a kernel application function
- Kernel fusion: applying $h \circ g \circ f$ on image with a kernel application function
  - Spare 4 of 6 image transfers
- Use iterator objects for stencil accesses
  - Hide in constructor caching of global memory block in local memory
  - Access to local memory instead

OpenCL SYCL road-map

`http://www.khronos.org/opencl/sycl`

- GDC (Game Developer Conference), March 2014
  - Released a provisional specification to enable feedback
  - Developers can provide input into standardization process
  - Feedback via Khronos forums
- Next steps
  - Full specification, based on feedback
  - Khronos test suite for implementations
  - Release of implementations
- Implementation
  - CodePlay
    `http://www.codeplay.com/portal/introduction-to-sycl`
- Prototype in progress
  - triSYCL `https://github.com/amd/triSYCL` ⤳ Join us!

SYCL summary

- Like C++AMP but with OpenCL/OpenGL/... interoperability
  - OpenCL data types and built-in functions available
  - Possible to optimize some parts in OpenCL
- Host “fall-back” mode
- Single source & C++11 even in kernel (with usual restrictions)
  - Generic kernel templates
  - Functional programming on operator ⇝ kernel fusion
- Errors through C++ exception handling
- Event handling through event class
- SYCL buffers are more abstract than OpenCL buffers
  - Data can reside on several accelerators
- `command_group` allows asynchronous task graphs *à la* StarPU
  - Read/write accessor declarations: edges of task dependence graph

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Outline

Conclusion

- Heterogeneous computing ⇝ Rewriting applications
  - Applications are to be refactored regularly anyway...
- Entry cost...
  - ∃ New tools allowing smooth integration in existing language
  - Can mix several approaches such as OpenMP + OpenCL + MPI
- Exit cost! ☹
  - Use Open Standards backed by Open Source implementations
  - Be locked or be free!
- Mobile computing is pushing!
- Advertising: French C++ User Group
  `http://www.meetup.com/User-Group-Cpp-Francophone`