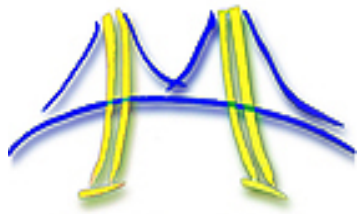
Hello World: Vector Addition

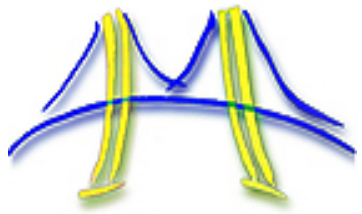


```
// Compute sum of length-N vectors: C = A + B
void
vecAdd (float* a, float* b, float* c, int N) {
    for (int i = 0; i < N; i++)
        c[i] = a[i] + b[i];
}

int main () {
    int N = ... ;
    float *a, *b, *c;
    a = new float[N];
  // ... allocate other arrays, fill with data


    vecAdd (a, b, c, N);
}
```

Hello World: Vector Addition

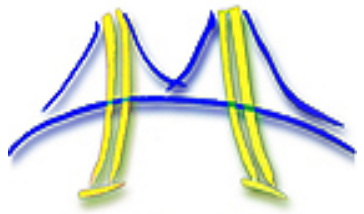


```
// Compute sum of length-N vectors: C = A + B
void __global__
vecAdd (float* a, float* b, float* c, int N) {
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    if (i < N) c[i] = a[i] + b[i];
}

int main () {
    int N = ... ;
    float *a, *b, *c;
    cudaMalloc (&a,  sizeof(float) * N);
  // ... allocate other arrays, fill with data

  // Use thread blocks with 256 threads each
    vecAdd <<< (N+255)/256, 256 >>> (a, b, c, N);
}
```

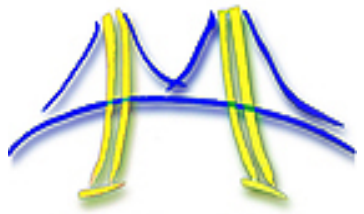
Cuda Software Environment



- nvcc compiler works much like icc or gcc: compiles C++ source code, generates binary executable
- Nvidia Cuda OS driver manages low-level interaction with device, provides API for C++ programs
- Nvidia Cuda SDK has many code samples demonstrating various Cuda functionalities
- Library support is continuously growing:
  - CUBLAS for basic linear algebra
  - CUFFT for Fourier Fransforms
  - CULapack (3rd party proprietary) linear solvers, eigensolvers, ...
- OS-Portable: Linux, Windows, Mac OS
- A lot of momentum in Industrial adoption of Cuda!

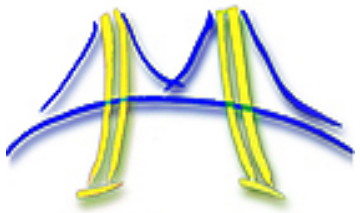
http://developer.nvidia.com/object/cuda_3_1_downloads.html

Agenda

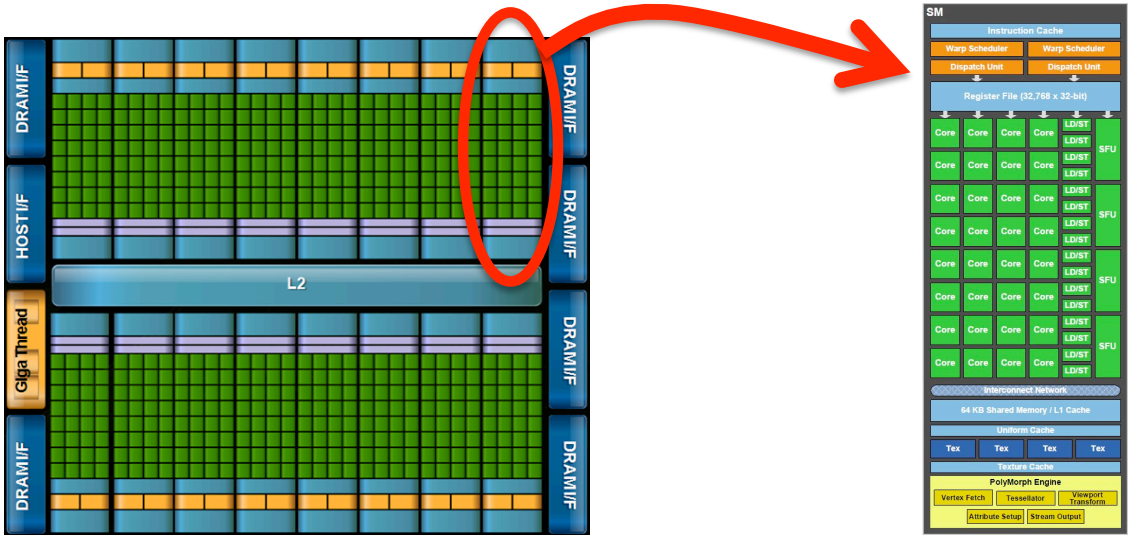


- A Shameless self-promotion
- Introduction to GPGPUs and Cuda Programming Model
- **The Cuda Thread Hierarchy**
- The Cuda Memory Hierarchy
- Mapping Cuda to Nvidia GPUs
- As much of the OpenCL information as I can get through

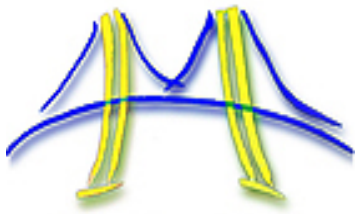
Nvidia Cuda GPU Architecture



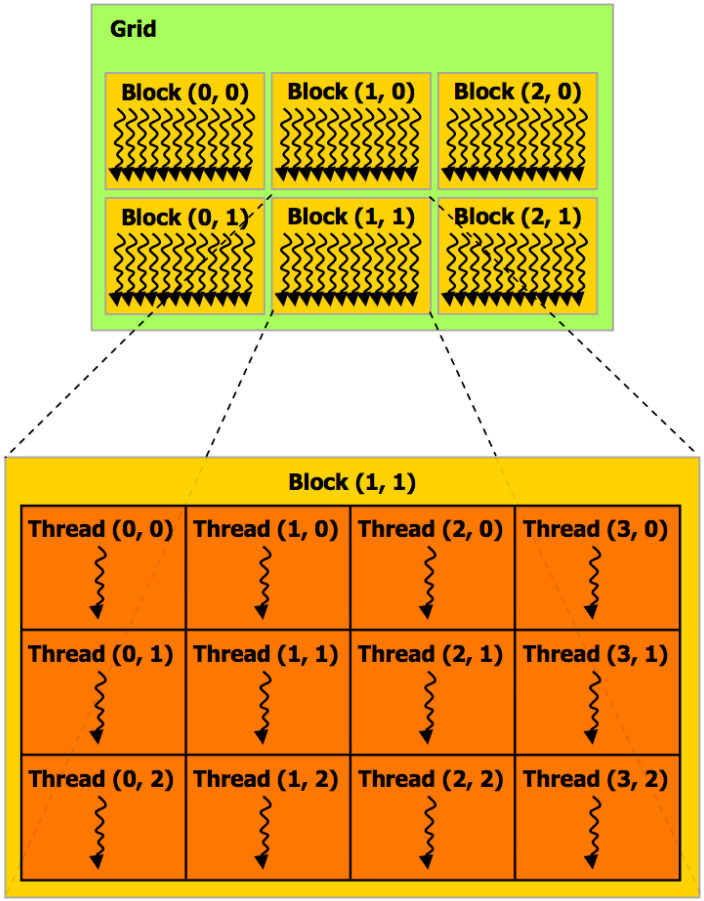
- I'll discuss some details of Nvidia's GPU architecture simultaneously with discussing the Cuda Programming Model
  - The Cuda Programming Model is a set of data-parallel extensions to C, amenable to implementation on GPUs, CPUs, FPGAs, ...
- Cuda GPUs are a collection of "Streaming Multiprocessors"
  - Each SM is analogous to a core of a Multi-Core CPU
- Each SM is a collection of SIMD execution pipelines (Scalar Processors) that share control logic, register file, and L1 Cache



Cuda Thread Hierarchy

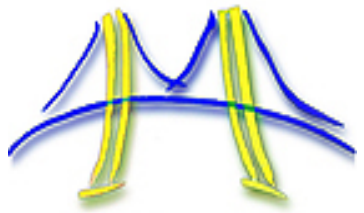


- Parallelism in the Cuda Programming Model is expressed as a 4-level Hierarchy:



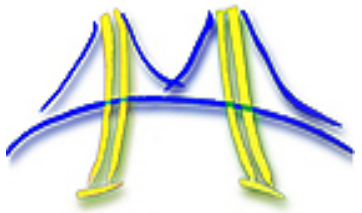
- A ***Stream*** is a list of ***Grids*** that execute in-order. Fermi GPUs execute multiple Streams in parallel
- A ***Grid*** is a set of up to 2^{32} ***Thread Blocks*** executing the same kernel
- A ***Thread Block*** is a set of up to 1024 [512 pre-Fermi] ***Cuda Threads***
- Each ***Cuda Thread*** is an independent, lightweight, scalar execution context
  - Groups of 32 threads form ***Warps*** that execute in lockstep SIMD

What is a Cuda Thread?

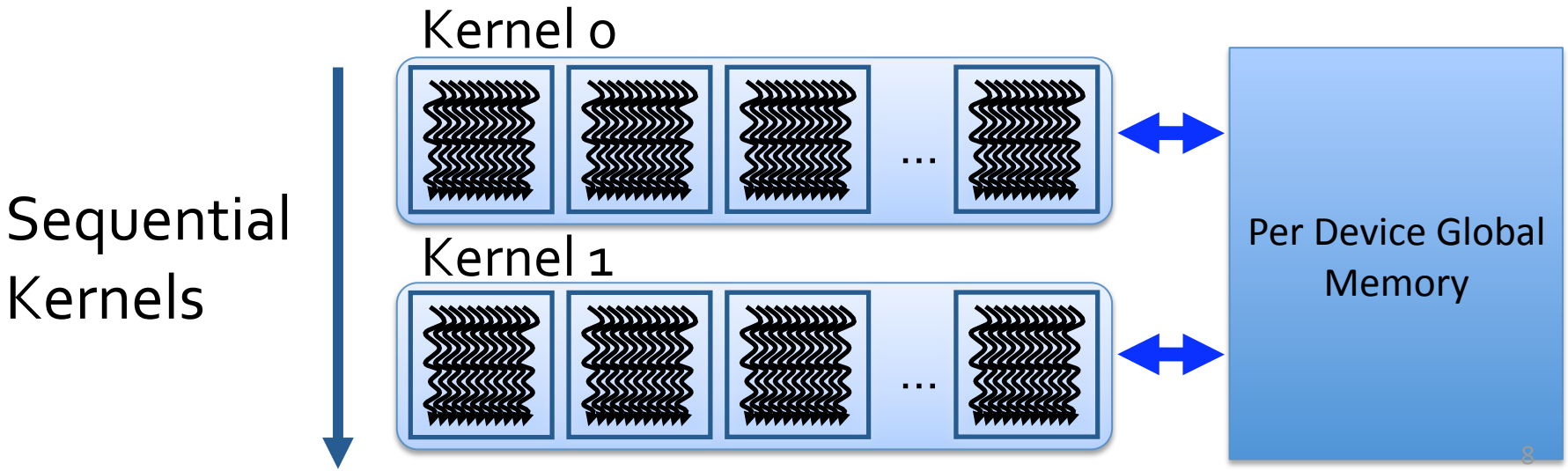


- Logically, each Cuda Thread is its own very lightweight **independent MIMD execution context**
  - Has its own control flow and PC, register file, call stack, ...
  - Can access any GPU global memory address at any time
  - Identifiable uniquely within a grid by the five integers: `threadIdx.{x,y,z}, blockIdx.{x,y}`
- **Very fine granularity**: do not expect any single thread to do a substantial fraction of an expensive computation
  - At full occupancy, each Thread has 21 32-bit registers
  - ... 1,536 Threads share a 64 KB L1 Cache / `__shared__` mem
  - GPU has no operand bypassing networks: functional unit latencies must be hidden by multithreading or ILP (e.g. from loop unrolling)

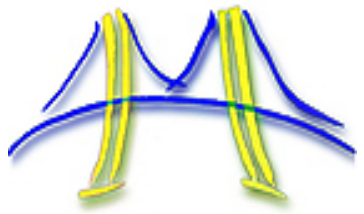
Cuda Memory Hierarchy



- Thread blocks in all Grids share access to a large pool of "Global" memory, separate from the Host CPU's memory.
  - Global memory holds the application's persistent state, while the thread-local and block-local memories are temporary
  - Global memory is much more expensive than on-chip memories: O(100)x latency, O(1/50)x (aggregate) bandwidth
- On Fermi, Global Memory is cached in a 768KB shared L2

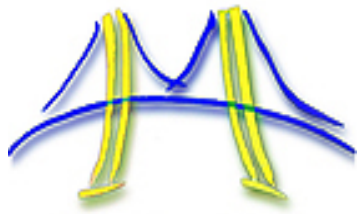


Cuda Memory Hierarchy

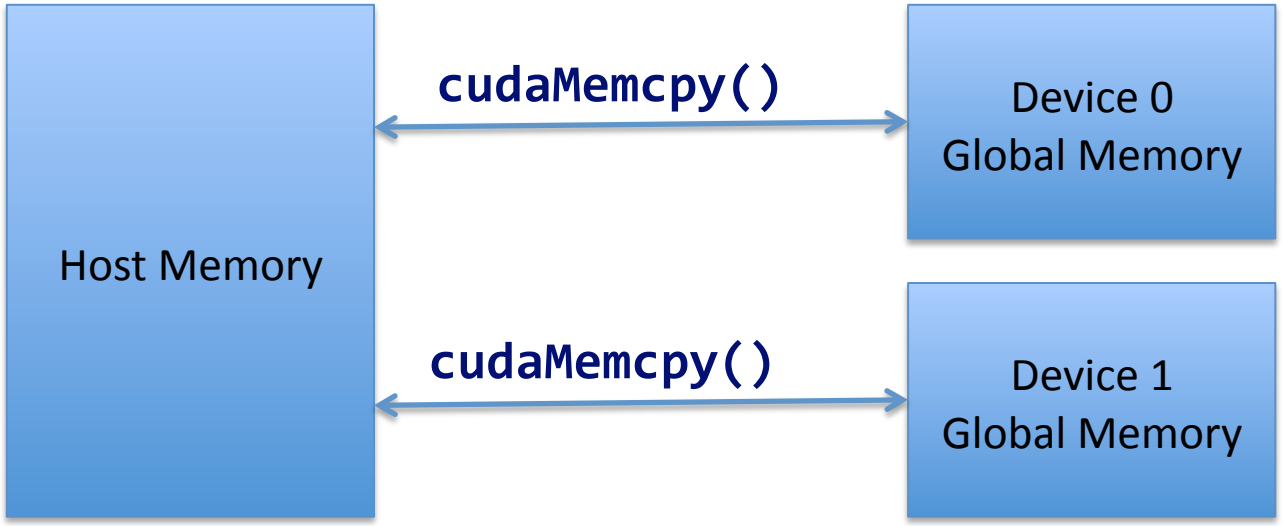


- There are other read-only components of the Memory Hierarchy that exist due to the Graphics heritage of Cuda
- The 64 KB Cuda **Constant Memory** resides in the same DRAM as global memory, but is accessed via special read-only 8 KB per-SM caches
- The Cuda **Texture Memory** also resides in DRAM and is accessed via small per-SM read-only caches, but also includes interpolation hardware
  - This hardware is crucial for graphics performance, but only occasionally is useful for general-purpose workloads
- The behaviors of these caches are highly optimized for their roles in graphics workloads.

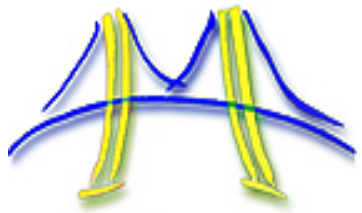
Cuda Memory Hierarchy



- Each Cuda device in the system has its own Global memory, separate from the Host CPU memory
  - Allocated via cudaMalloc()/cudaFree() and friends
- Host ⇔ Device memory transfers are via cudaMemcpy() over PCI-E, and are extremely expensive
  - microsecond latency, ~GB/s bandwidth
- Multiple Devices managed via multiple CPU threads



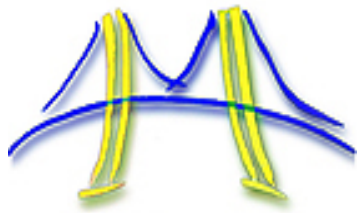
Thread-Block Synchronization



- Intra-block barrier instruction `__syncthreads()` for synchronizing accesses to `__shared__` and global memory
  - To guarantee correctness, must `__syncthreads()` before reading values written by other threads
  - All threads in a block must execute the same `__syncthreads()`, or the GPU will hang (not just the same number of barriers !)
- Additional intrinsics worth mentioning here:
  - `int __syncthreads_count(int), int __syncthreads_and(int), int __syncthreads_or(int)`

```
extern __shared__ float T[];
__device__ void
transpose (float* a, int lda){
    int i = threadIdx.x, j = threadIdx.y;
    T[i + lda*j] = a[i + lda*j];
    __syncthreads();
    a[i + lda*j] = T[j + lda*i];
}
```

Using per-block shared memory



- The per-block shared memory / L1 cache is a crucial resource: without it, the performance of most Cuda programs would be hopelessly DRAM-bound
- Block-shared variables can be declared statically:

```
__shared__ int begin, end;
```

- Software-managed scratchpad is allocated statically:

```
__shared__ int scratch[128];
scratch[threadIdx.x] = ... ;
```

- ... or dynamically:

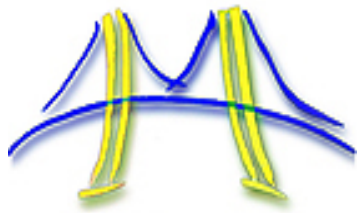
```
extern __shared__ int scratch[];

kernel_call <<< grid_dim, block_dim, scratch_size >>> ( ... );
```

- Most intra-block communication is via shared scratchpad:

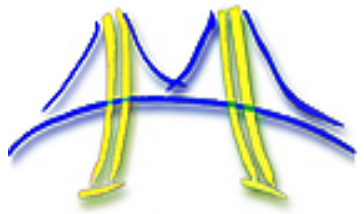
```
scratch[threadIdx.x] = ...;
__syncthreads();
int left = scratch[threadIdx.x - 1];
```

Using per-block shared memory



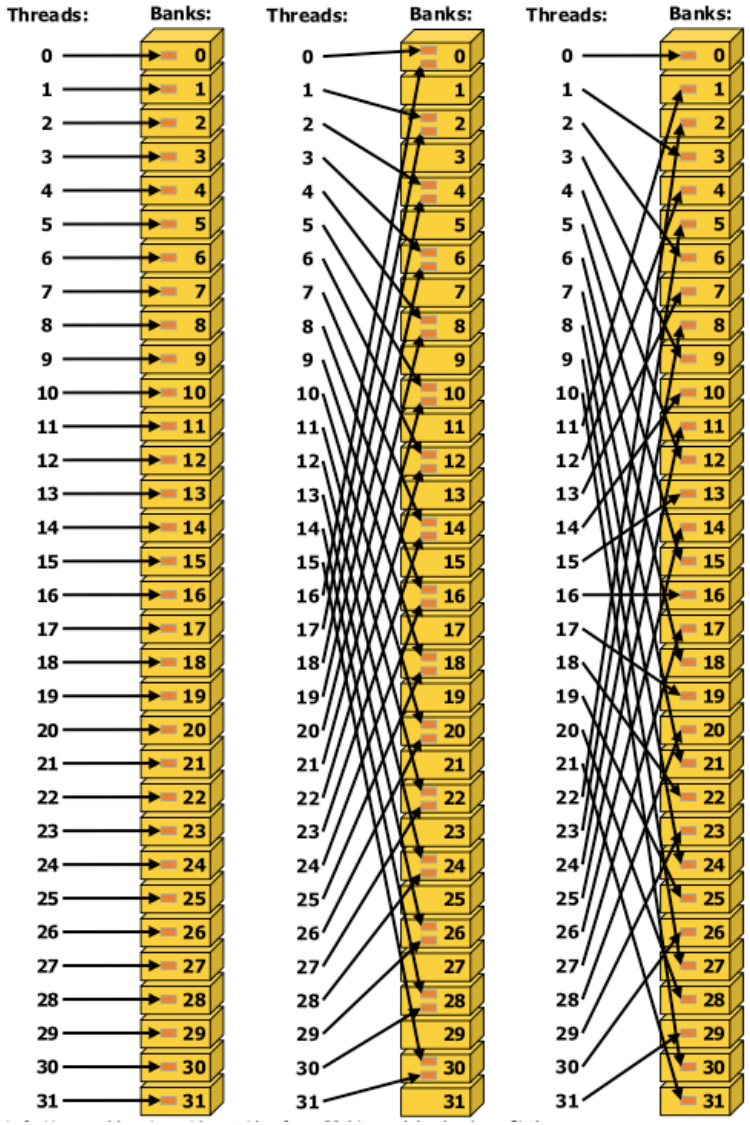
- Each SM has 64 KB of private memory, divided 16KB/48KB (or 48KB/16KB) into software-managed scratchpad and hardware-managed, non-coherent cache
  - Pre-Fermi, the SM memory is only 16 KB, and is usable only as software-managed scratchpad
- Unless data will be shared between Threads in a block, it should reside in registers
  - On Fermi, the 128 KB Register file is twice as large, and accessible at higher bandwidth and lower latency
  - Pre-Fermi, register file is 64 KB and equally fast as scratchpad

Shared Memory Bank Conflicts



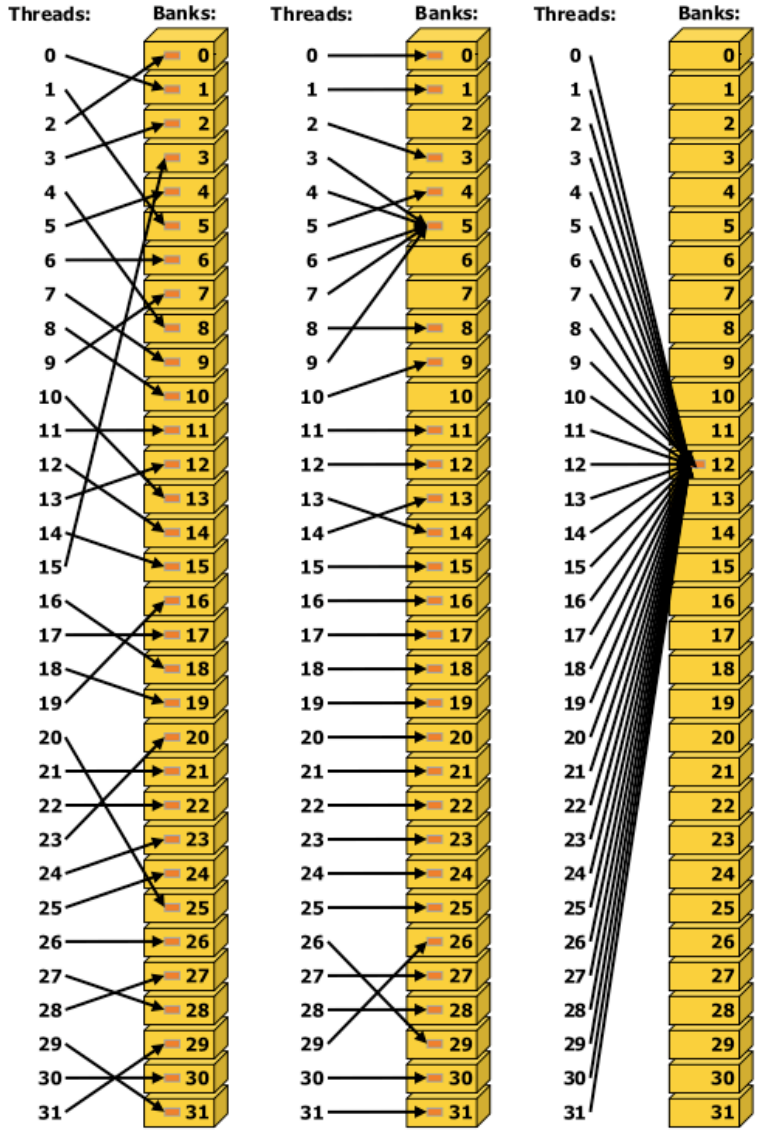
- Shared memory is ***banked***: it consists of 32 (16, pre-Fermi) independently addressable 4-byte wide memories
  - Addresses interleave: **`float *p`** points to a float in bank ***k,*** **`p+1`** points to a float in bank ***(k+1) mod 32***
- Each bank can satisfy a single 4-byte access per cycle.
  - A ***bank conflict*** occurs when two threads (in the same warp) try to access the same bank in a given cycle.
  - The GPU hardware will execute the two accesses serially, and the warp's instruction will take an extra cycle to execute.
- Bank conflicts are a second-order performance effect: even serialized accesses to on-chip shared memory is faster than accesses to off-chip DRAM

Shared Memory Bank Conflicts



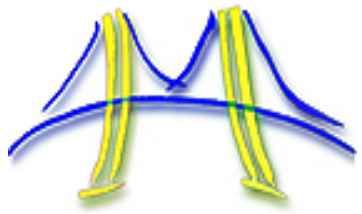
- Figure G-2 from Cuda C Programming Gude 3.1
- Unit-Stride access is **conflict-free**
- Stride-2 access: thread ***n*** conflicts with thread ***16+n***
- Stride-3 access is **conflict-free**

Shared Memory Bank Conflicts



- Three more cases of conflict-free access
  - Figure G-3 from Cuda C Programming Gude 3.1
- Permuations within a 32-float block are OK
- Multiple threads reading the **same memory address**
- **All threads** reading the same memory address is a ***broadcast***

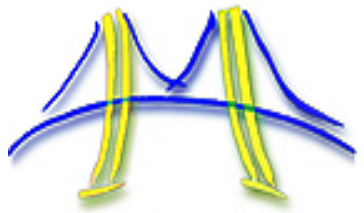
Atomic Memory Operations



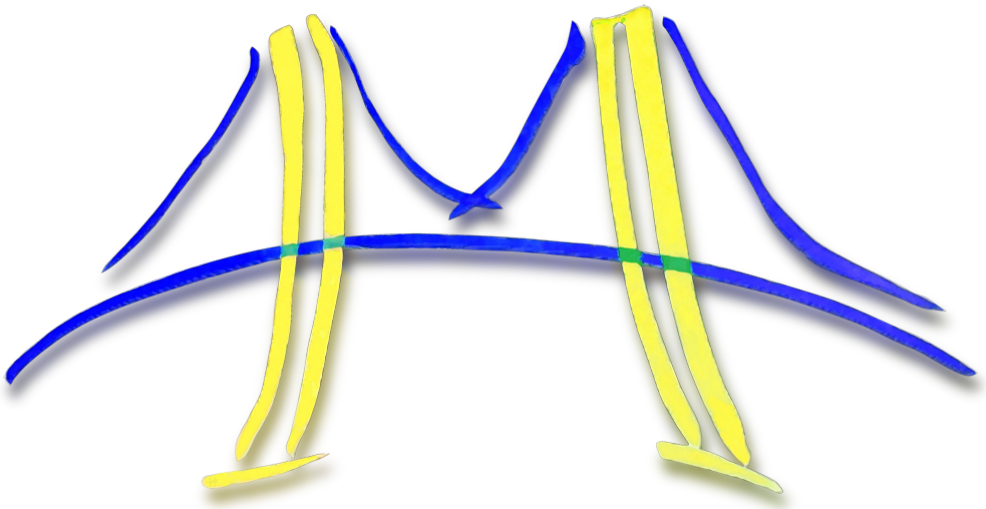
- Cuda provides a set of instructions which execute atomically with respect to each other
  - Allow non-read-only access to variables shared between threads in shared or global memory
  - Substantially more expensive than standard load/stores
  - Wth voluntary consistency, can implement e.g. spin locks!

```
int atomicAdd (int*,int), float atomicAdd (float*, float), ...
...
int atomicMin (int*,int),
...
int atomicExch (int*,int), float atomicExch (float*,float), ...
int atomicCAS (int*, int compare, int val), ...
```

Voluntary Memory Consistency

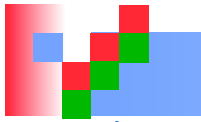


- By default, you cannot assume memory accesses are occur in the same order specified by the program
  - Although a thread's ***own*** accesses appear to that thread to occur in program order
- To enforce ordering, use ***memory fence*** instructions
  - `__threadfence_block()`: make all previous memory accesses visible to all other threads ***within the thread block***
  - `__threadfence()`: make previous ***global*** memory accesses visible to all other threads ***on the device***
- Frequently must also use the `volatile` type qualifier
  - Has same behavior as CPU C/C++: the compiler is forbidden from register-promoting values in volatile memory
  - Ensures that pointer dereferences produce load/store instructions
  - Declared as `volatile float *p;` `*p` must produce a memory ref.

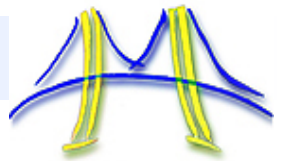


Introduction to OpenCL

Tim Mattson
Microprocessor and Programming Research Lab
Intel Corp.



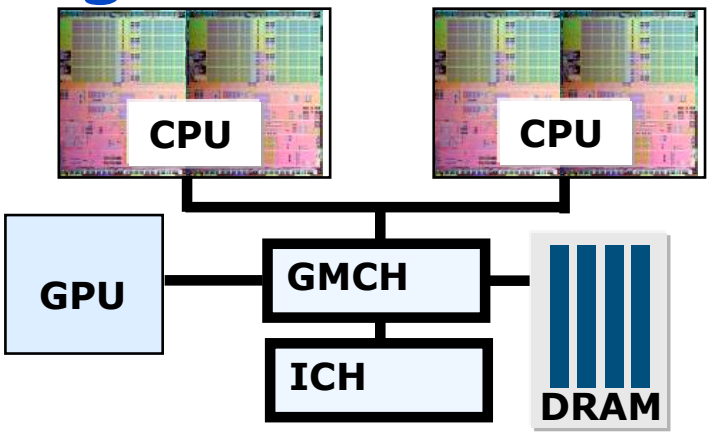
Agenda



- Ugly programming models and why they rule
- The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- An OpenCL "deep dive"

Heterogeneous computing

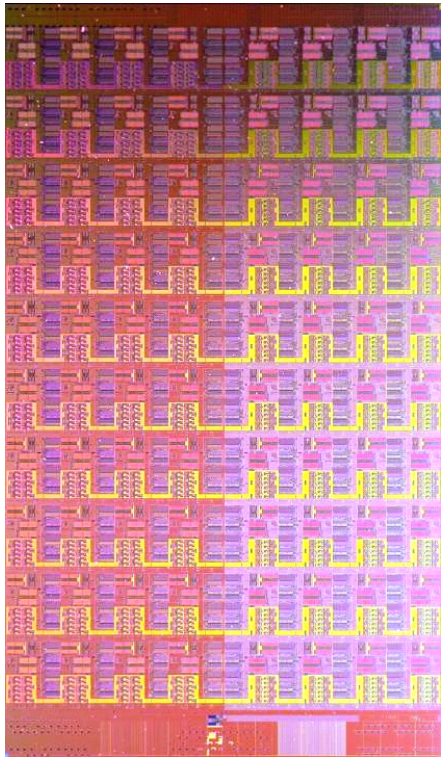
- A modern platform has:
  - Multi-core CPU(s)
  - A GPU
  - DSP processors
  - … other?



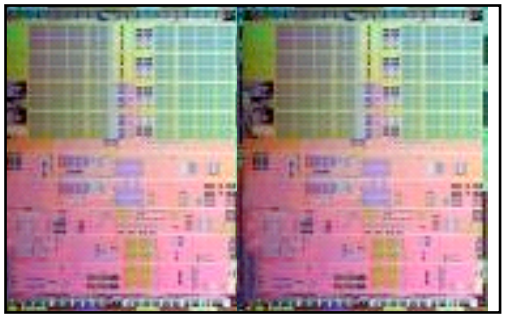
- The goal should NOT be to "off-load" the CPU. We need to make the best use of all the available resources from within a single program:
  - One program that runs well (i.e. reasonably close to "hand-tuned" performance) on a heterogeneous mixture of processors.

Heterogeneous many core processors

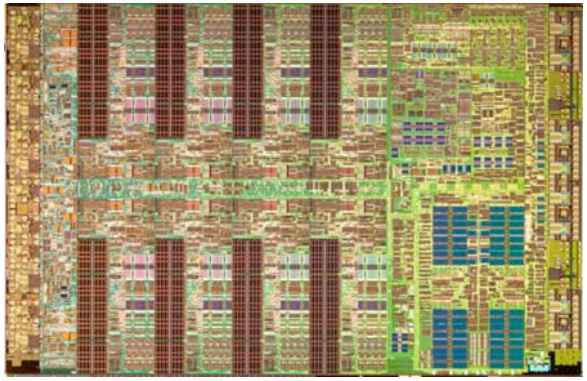
The mass market hardware landscape has never been so chaotic … and its only going to get worse.



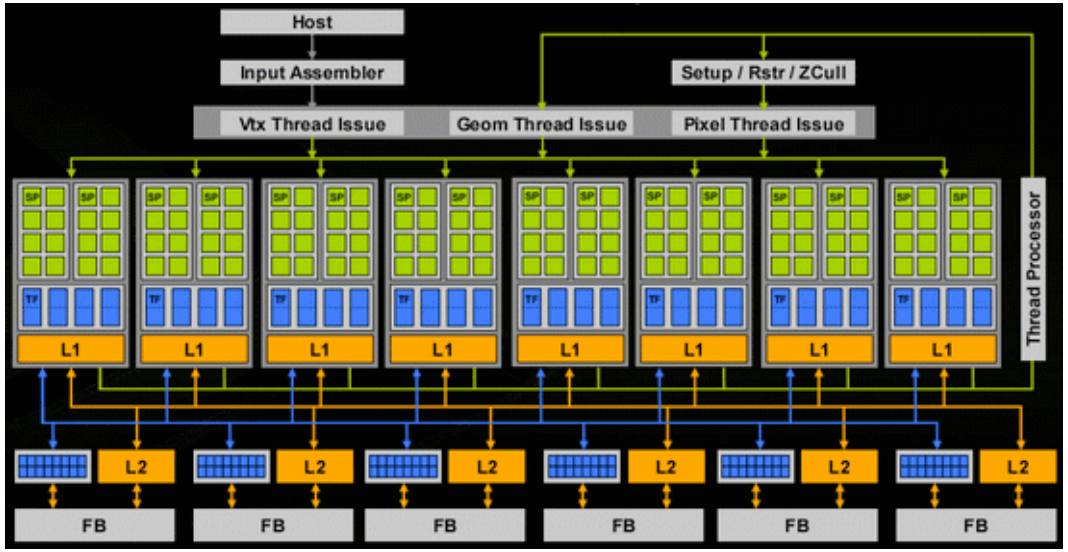
Intel 80 core research chip



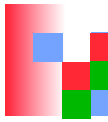
Intel Dual Core CPU

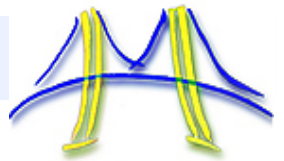


IBM Cell



NVIDIA 8800

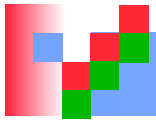


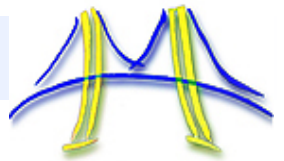


The many-core challenge

- We have arrived at many-core solutions not because of the success of our parallel software but because of our failure to keep increasing CPU frequency.
- Result: a fundamental and dangerous mismatch
  - Parallel hardware is ubiquitous.
  - Parallel software is rare

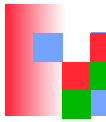
Our challenge … make parallel software as routine as our parallel hardware.

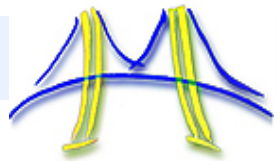




Patterns and Frameworks

- In the long run, we will provide high level frameworks/scripting-languages that will meet the needs of the domain-expert, application programmers (we hope).
  - Design patterns will guide us to the right framework designs.
- But even in a frameworks world, you need to support the framework programmers
  - (also known as efficiency programmers, technology programmers, socially mal-adjusted performance hackers, etc)
- How do we support these low-level "performance obsessed" programmers?





Solution: Find A Good parallel programming model, right?

ABCPL
ACE
ACT++
Active messages
Adl
Adsmith
ADDAP
AFAPI
ALWAN
AM
AMDC
AppLeS
Amoeba
ARTS
Athapascan-0b
Aurora
Automap
bb_threads
Blaze
BSP
BlockComm
C*.
"C* in C
C**
CarlOS
Cashmere
C4
CC++
Chu
Charlotte
Charm
Charm++
Cid
Cilk
CM-Fortran
Converse
Code
COOL

CORRELATE
CPS
CRL
CSP
Cthreads
CUMULVS
DAGGER
DAPPLE
Data Parallel C
DC++
DCE++
DDD
DICE.
DIPC
DOLIB
DOME
DOSMOS.
DRL
DSM-Threads
Ease .
ECO
Eiffel
Eilean
Emerald
EPL
Excalibur
Express
Falcon
Filaments
FM
FLASH
The FORCE
Fork
Fortran-M
FX
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GAMMA
Glenda

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Haskell
HPC++
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ISIS.
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Java RMI
javaPG
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Joyce
Khoros
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Lilac
Linda
JADA
WWWinda
ISETL-Linda
ParLin
Eilean
P4-Linda
POSYBL
Objective-Linda
LiPS
Locust
Lparx
Lucid
Maisie
Manifold

Mentat
Legion
Meta Chaos
Midway
Millipede
CparPar
Mirage
MpC
MOSIX
Modula-P
Modula-2*
Multipol
MPI
MPC++
Munin
Nano-Threads
NESL
NetClasses++
Nexus
Nimrod
NOW
Objective Linda
Occam
Omega
OpenMP
Orca
OOF90
P++
P3L
Pablo
PADE
PADRE
Panda
Papers
AFAPI.
Para++
Paradigm

Parafrase2
Paralation
Parallel-C++
Parallaxis
ParC
ParLib++
ParLin
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Parti
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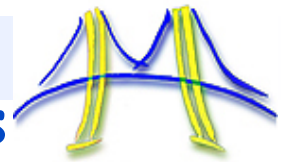
POOMA
POOL-T
PRESTO
P-RIO
Prospero
Proteus
QPC++
PVM
PSI
PSDM
Quake
Quark
Quick Threads
Sage++
SCANDAL
SAM

pC++
SCHEDULE
SciTL
SDDA.
SHMEM
SIMPLE
Sina
SISAL.
distributed smalltalk
SMI.
SONiC
Split-C.
SR
Sthreads
Strand.
SUIF.
Synergy
Telegrphos
SuperPascal
TCGMSG.
Threads.h++.
TreadMarks
TRAPPER
uC++
UNITY
UC
V
ViC*
Visifold V-NUS
VPE
Win32 threads
WinPar
XENOOPS
XPC
Zounds
ZPL

Models from the golden age of parallel programming

The only thing sillier than creating too many models is using too many



ABCPL
ACE
ACT++
Active messages
Adl
Adsmith
ADDAP
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ALWAN
AM
AMDC
AppLeS
Amoeba
ARTS
Athapascan-0b
Aurora
Automap
bb_threads
Blaze
BSP
BlockComm
C*.
"C* in C
C**
CarlOS
Cashmere
C4
CC++
Chu
Charlotte
Charm
Charm++
Cid
Cilk
CM-Fortran
Converse
Code
COOL

CORRELATE
CPS
CRL
CSP
Cthreads
CUMULVS
DAGGER
DAPPLE
Data Parallel C
DC++
DCE++
DDD
DICE.
DIPC
DOLIB
DOME
DOSMOS.
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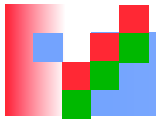
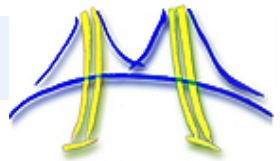
Programming models I've worked with.

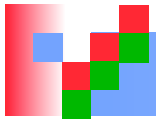


There is nothing new under the sun

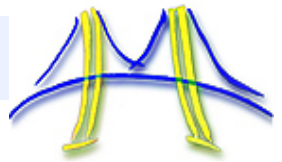


- Message passing models:
  - MPI PVM
- Data Parallel programming models
  - C* HPF NESL CMFortran
- Virtual Shared Memory models
  - Linda GA
- Functional Languages
  - Haskell SISAL
- Formal compositional models
  - CC++ PCN
- Shared address space … threads
  - OpenMP Cilk
- Parallel object Oriented programming
  - Mentat CHARM++ POOMA TBB

Parallel programming …
"been there, done that"
Will we be wise enough to learn from the past?

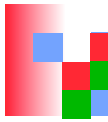


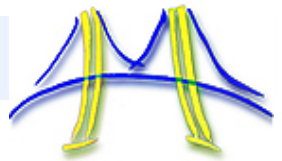
Lesson 1: computer scientists are easily seduced by beauty



- A beautiful programming model:
  - Safe: its hard to do bad things
  - Expressive: focus on the intent of the algorithm.
  - Abstract: Hides hardware details
  - Novel: New ideas and fresh perspectives

To the computer scientist … There is no problem that can't be solved by adding another layer of abstraction.
The history of parallel programming can be viewed as computer scientists chasing after an elusive ideal of beauty





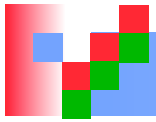
Lesson 2: Software vendors (not academics and not hardware vendors) choose the winning programming models

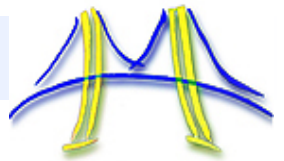
- What software developers need:
  - Portability: recompile to run on every platform the market demands
  - Stability: program life times measured in decades.
  - Predictability: the ability to build code that adapts to hardware details for predictable performance.

Industry standards with minimal HW constraints

Established prog. Envs. from long term, trusted sources

HW details exposed so SW can adapt

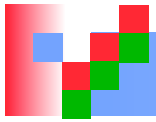




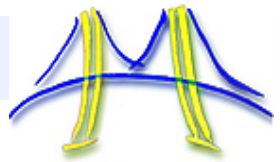
Ugly programming models win!

- Software developers only weakly care about beauty in a programming model … pragmatism wins.
- History supports ugly programming models … with all the elegant abstractions for parallelism that have been created, what is actually used:
  - MPI
  - Explicit thread libraries
  - Compiler directives

OpenCL is truly ugly … and to support our framework developers facing heterogenous many core platforms, its exactly what we need!

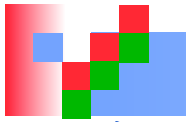


How ugly is OpenCL?

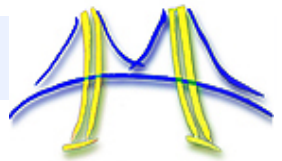


… just look at all the built-in fuctions we had to define to make this thing work?

Math Functions
gentype acos (gentype)
gentype acosh (gentype)
gentype acospi (gentype x)
gentype asin (gentype)
gentype asinh (gentype)
gentype asinpi (gentype x)
gentype atan (gentype y_over_x)
gentype atan2 (gentype y, gentype x)
gentype atanh (gentype)
gentype atanpi (gentype x)
gentype atan2pi (gentype y, gentype x)
gentype cbrt (gentype)
gentype ceil (gentype)
gentype copysign (gentype x, gentype y)
gentype cos (gentype)
gentype cosh (gentype)
gentype cospi (gentype x)
gentype erfc (gentype)
gentype erf (gentype)
gentype exp (gentype x)
gentype exp2 (gentype)
gentype exp10 (gentype)
gentype expm1 (gentype x)
gentype fabs (gentype)
gentype fdim (gentype x, gentype y)
gentype floor (gentype)
gentype fma (gentype a, gentype b, gentype c)
gentype fmax (gentype x, gentype y)
gentype fmax (gentype x, float y)
gentype fmin (gentype x, gentype y)
gentype fmin (gentype x, float y)
gentype fmod (gentype x, gentype y)
gentype fract (gentype x, gentype *iptr)
gentype frexp (gentype x, intn *exp)
gentype hypot (gentype x, gentype y)
intn ilogb (gentype x)
gentype ldexp (gentype x, intn n)
gentype ldexp (gentype x, int n)
gentype lgamma (gentype x)
gentype lgamma_r (gentype x, intn *signp)
gentype log (gentype)
gentype log2 (gentype)
gentype log10 (gentype)
gentype log1p (gentype x)
gentype logb (gentype x)
gentype mad (gentype a, gentype b, gentype c)
gentype modf (gentype x, gentype *iptr)
gentype nan (uintn nancode)
gentype nextafter (gentype x, gentype y)
gentype pow (gentype x, gentype y)
gentype pown (gentype x, intn y)
gentype powr (gentype x, gentype y)
gentype remainder (gentype x, gentype y)
gentype remquo (gentype x, gentype y, intn *quo)
gentype rint (gentype)
gentype rootn (gentype x, intn y)
gentype round (gentype x)
gentype rsqrt (gentype)
gentype sin (gentype)
gentype sincos (gentype x, gentype *cosval)
gentype sinh (gentype)
gentype sinpi (gentype x)
gentype sqrt (gentype)
gentype tan (gentype)
gentype tanh (gentype)
gentype tanpi (gentype x)
gentype tgamma (gentype)
gentype trunc (gentype)
Integer Ops
ugentype abs (gentype x)
ugentype abs_diff (gentype x, gentype y)
gentype add_sat (gentype x, gentype y)
gentype hadd (gentype x, gentype y)
gentype rhadd (gentype x, gentype y)
gentype clz (gentype x)
gentype mad_hi (gentype a, gentype b, gentype c)
gentype mad_sat (gentype a, gentype b, gentype c)
gentype max (gentype x, gentype y)
gentype min (gentype x, gentype y)
gentype mul_hi (gentype x, gentype y)
gentype rotate (gentype v, gentype i)
gentype sub_sat (gentype x, gentype y)
shortn upsample (intn hi, uintn lo)
ushortn upsample (uintn hi, uintn lo)
intn upsample (intn hi, uintn lo)
uintn upsample (uintn hi, uintn lo)
longn upsample (intn hi, uintn lo)
ulongnn upsample (uintn hi, uintn lo)
gentype mad24 (gentype x, gentype y, gentype z)
gentype mul24 (gentype x, gentype y)
Common Functions
gentype clamp (gentype x, gentype minval, gentype maxval)
gentype clamp (gentype x, float minval, float maxval)
gentype degrees (gentype radians)
gentype max (gentype x, gentype y)
gentype max (gentype x, float y)
gentype min (gentype x, gentype y)
gentype min (gentype x, float y)
gentype mix (gentype x, gentype y, gentype a)
gentype mix (gentype x, gentype y, float a)
gentype radians (gentype degrees)
gentype sign (gentype x)
Geometric Functions
float4 cross (float4 p0, float4 p1)
float dot (gentype p0, gentype p1)
float distance (gentype p0, gentype p1)
float length (gentype p)
float fast_distance (gentype p0, gentype p1)
float fast_length (gentype p)
gentype fast_normalize (gentype p)
Relational Ops
int isequal (float x, float y)
intn isequal (floatn x, floatn y)
int isnotequal (float x, float y)
intn isnotequal (floatn x, floatn y)
int isgreater (float x, float y)
intn isgreater (floatn x, floatn y)
int isgreaterequal (float x, float y)
intn isgreaterequal (floatn x, floatn y)
int isless (float x, float y)
intn isless (floatn x, floatn y)
int islessequal (float x, float y)
intn islessequal (floatn x, floatn y)
int islessgreater (float x, float y)
intn islessgreater (floatn x, floatn y)
int isfinite (float)
intn isfinite (floatn)
int isnan (float)
intn isnan (floatn)
int isnormal (float)
intn isnormal (floatn)
int isordered (float x, float y)
intn isordered (floatn x, floatn y)
int isunordered (float x, float y)
intn isunordered (floatn x, floatn y)
int signbit (float)
intn signbit (floatn)
int any (igentype x)
int all (igentype x)
gentype bitselect (gentype a, gentype b, gentype c)
gentype select (gentype a, gentype b,igentype c)
gentype select (gentype a, gentype b,ugentype c)
Vector Loads/Store Functions
gentypen vloadn (size_t offset, const global gentype *p)
gentypen vloadn (size_t offset, const __local gentype *p)
gentypen vloadn (size_t offset, const __constant gentype *p)
gentypen vloadn (size_t offset, const __private gentype *p)
void vstoren (gentypen data, size_t offset, global gentype *p)
void vstoren (gentypen data, size_t offset, __local gentype *p)
void vstoren (gentypen data, size_t offset, __private gentype *p)
void vstore_half (float data, size_t offset, global half *p)
void vstore_half_rte (float data, size_t offset, global half *p)
void vstore_half_rtz (float data, size_t offset, global half *p)
void vstore_half_rtp (float data, size_t offset, global half *p)
void vstore_half_rtn (float data, size_t offset, global half *p)
void vstore_half (float data, size_t offset, __local half *p)
void vstore_half_rte (float data, size_t offset, __local half *p)
void vstore_half_rtz (float data, size_t offset, __local half *p)
void vstore_half_rtp (float data, size_t offset, __local half *p)
void vstore_half_rtn (float data, size_t offset, __local half *p)
void vstore_half (float data, size_t offset, __private half *p)
void vstore_half_rte (float data, size_t offset, __private half *p)
void vstore_half_rtz (float data, size_t offset, __private half *p)
void vstore_half_rtp (float data, size_t offset, __private half *p)
void vstore_half_rtn (float data, size_t offset, global half *p)
void vstore_halfn (floatn data, size_t offset, global half *p)
void vstore_halfn_rte (floatn data, size_t offset, global half *p)
void vstore_halfn_rtz (floatn data, size_t offset, global half *p)
void vstore_halfn_rtp (floatn data, size_t offset, global half *p)
void vstore_halfn_rtn (floatn data, size_t offset, global half *p)
void vstore_halfn (floatn data, size_t offset, __local half *p)
void vstore_halfn_rte (floatn data, size_t offset, __local half *p)
void vstore_halfn_rtz (floatn data, size_t offset, __local half *p)
void vstore_halfn_rtp (floatn data, size_t offset, __local half *p)
void vstore_halfn_rtn (floatn data, size_t offset, __local half *p)
void vstore_halfn (floatn data, size_t offset, __private half *p)
void vstore_halfn_rte (floatn data, size_t offset, __private half *p)
void vstore_halfn_rtz (floatn data, size_t offset, __private half *p)
void vstore_halfn_rtp (floatn data, size_t offset, __private half *p)
void vstore_halfn_rtn (floatn data, size_t offset, __private half *p)
void vstorea_halfn (floatn data, size_t offset, global half *p)
void vstorea_halfn_rte (floatn data, size_t offset, global half *p)
void vstorea_halfn_rtz (floatn data, size_t offset, global half *p)
void vstorea_halfn_rtp (floatn data, size_t offset, global half *p)
void vstorea_halfn_rtn (floatn data, size_t offset, global half *p)
void vstorea_halfn (floatn data, size_t offset, __local half *p)
void vstorea_halfn_rte (floatn data, size_t offset, __local half *p)
void vstorea_halfn_rtz (floatn data, size_t offset, __local half *p)
void vstorea_halfn_rtp (floatn data, size_t offset, __local half *p)
void vstorea_halfn_rtn (floatn data, size_t offset, __local half *p)
void vstorea_halfn (floatn data, size_t offset, __private half *p)
void vstorea_halfn_rte (floatn data, size_t offset, __private half *p)
void vstorea_halfn_rtz (floatn data, size_t offset, __private half *p)
void vstorea_halfn_rtp (floatn data, size_t offset, __private half *p)
void vstorea_halfn_rtn (floatn data, size_t offset, __private half *p)

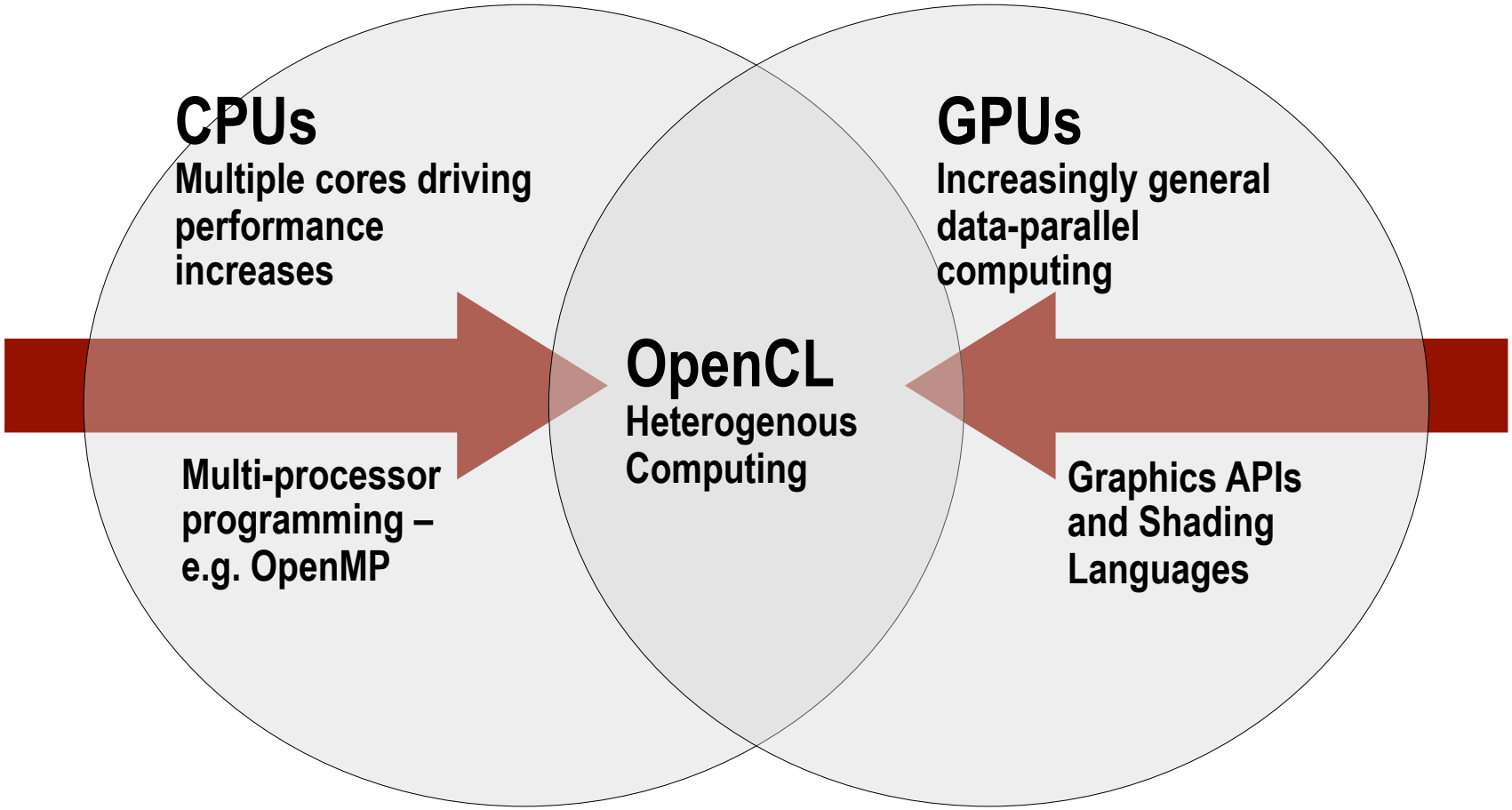


Agenda



- Ugly programming models and why they rule
- The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- An OpenCL "deep dive"

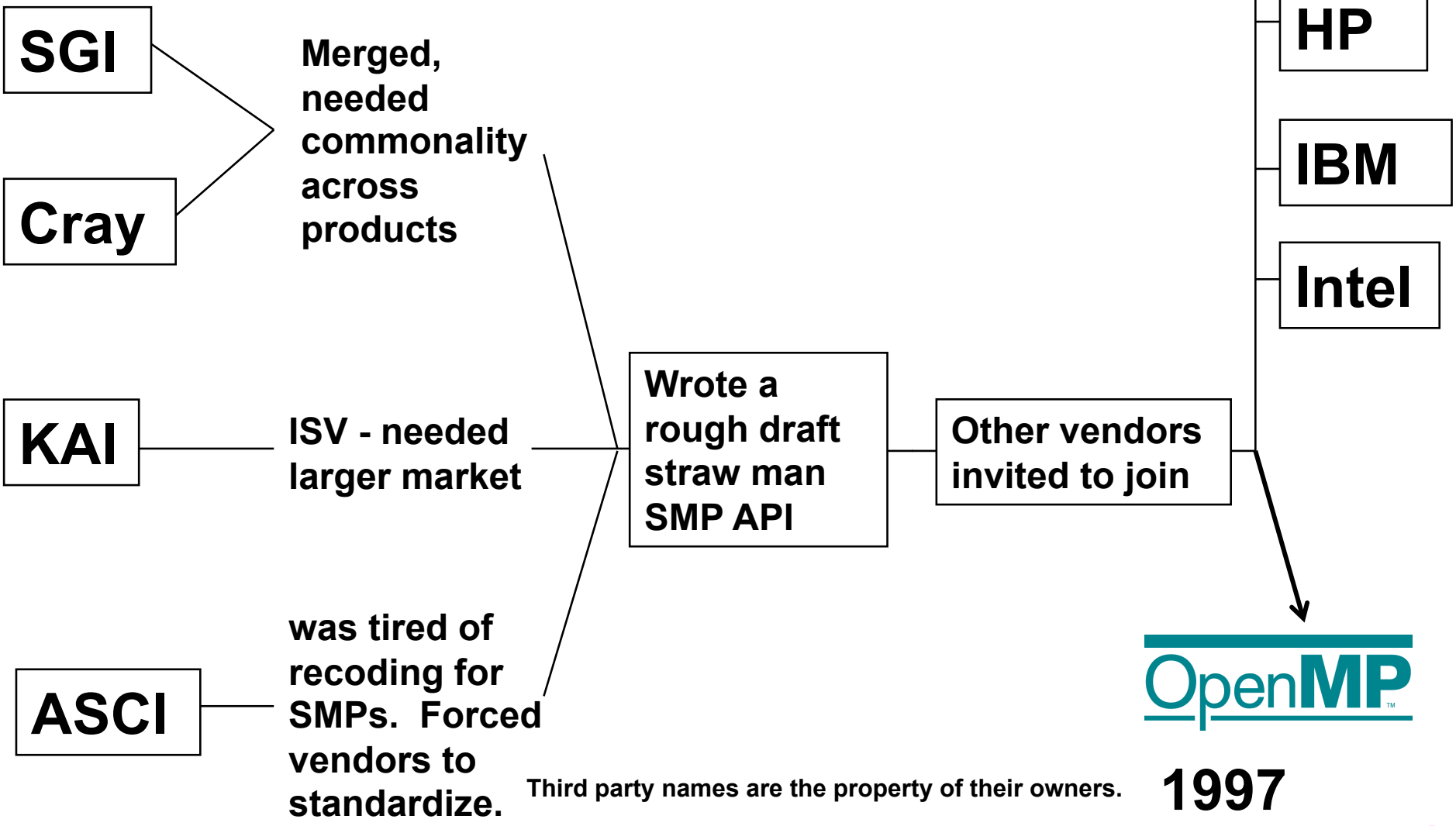
OpenCL … the ugliest programming model in existence



OpenCL – Open Computing Language

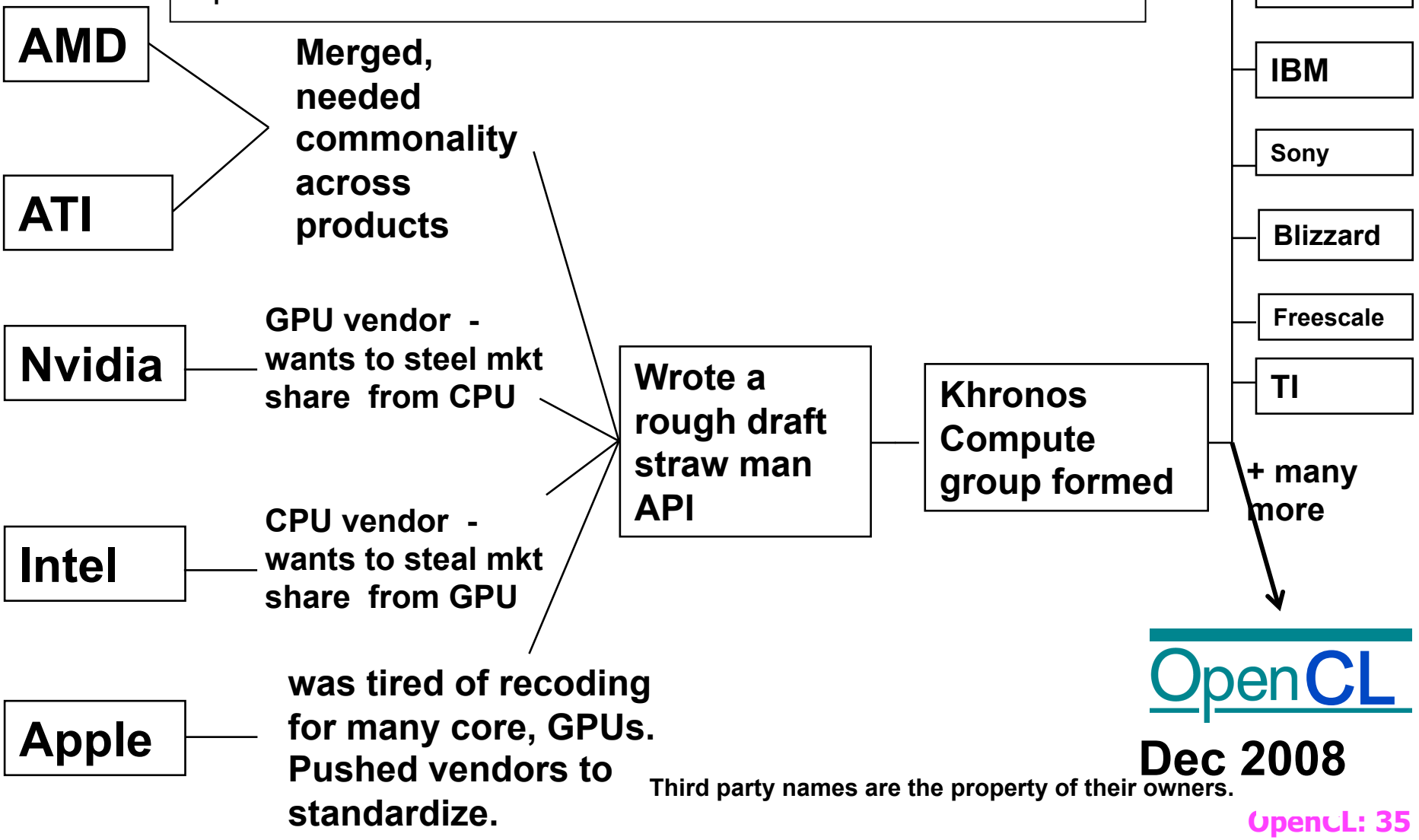
Open standard for portable programming of heterogeneous platforms (CPUs, GPUs, and other processors)

Consider the historical precedent with OpenMP …

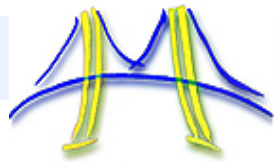


OpenCL: Can history repeat itself?

As ASCI did for OpenMP, Apple is doing for GPU/CPU with OpenCL



OpenCL Working Group

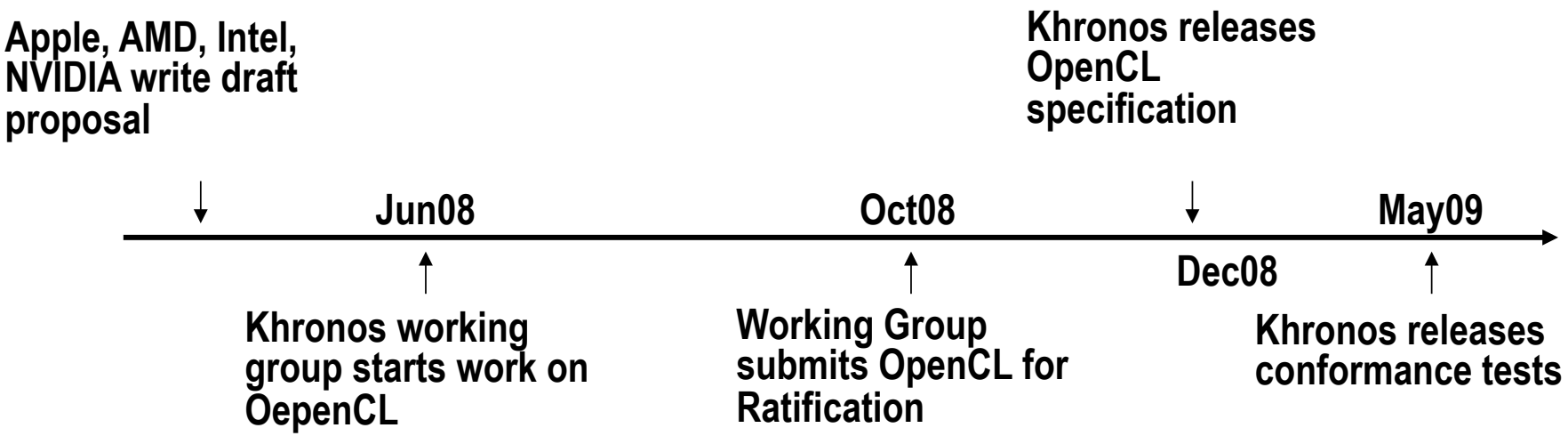


- Designed with real users (Apple + ISVs) to solve their problems.
- Used Khronos to make it an industry standard.

3DLABS SEMICONDUCTOR
ACTIVISION BLIZZARD
AMD
ARM
BROADCOM
EA
codeplay
ERICSSON
freescale semiconductor
HI CORP.
IBM
intel
Imagination TECHNOLOGIES
Los Alamos NATIONAL LABORATORY
MOTOROLA
movidia
NOKIA
NVIDIA
QNX SOFTWARE SYSTEMS
RAPIDMIND
SAMSUNG
Seaweed SYSTEMS
TAKUMI
TEXAS INSTRUMENTS
UMEÅ UNIVERSITET

KHRONOS GROUP

OpenCL Timeline



- Six months from proposal to released specification
- Commercial support:
  - Apple's Mac OS X Snow Leopard (9'2009) will include OpenCL.
  - Nvidia OpenCL beta release on CUDA.
  - AMD rleased a CPU OpenCL SIGGRAPH'09
  - Intel actively promotes OpenCL, but we have not announced our product strategy for OpenCL yet.

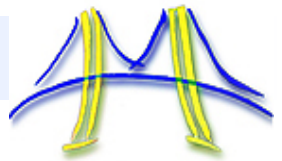
OpenCL 1.0 Embedded Profile

- Enables OpenCL on mobile and embedded silicon
  - Relaxes some data type and precision requirements
  - Avoids the need for a separate “ES” specification
- Khronos APIs provide computing support for imaging & graphics
  - Enabling advanced applications in, e.g., Augmented Reality
- OpenCL will enable parallel computing in new markets
  - Mobile phones, cars, avionics

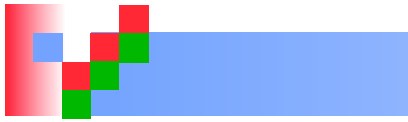
A camera phone with GPS processes images to recognize buildings and landmarks and provides relevant data from internet

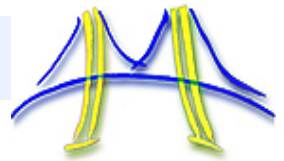
Source: Kari Pulli, Nokia

Agenda



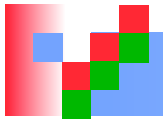
- Ugly programming models and why they rule
- The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- An OpenCL "deep dive"

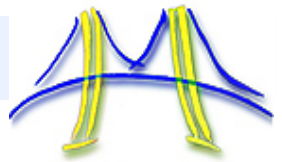




OpenCL: high level view

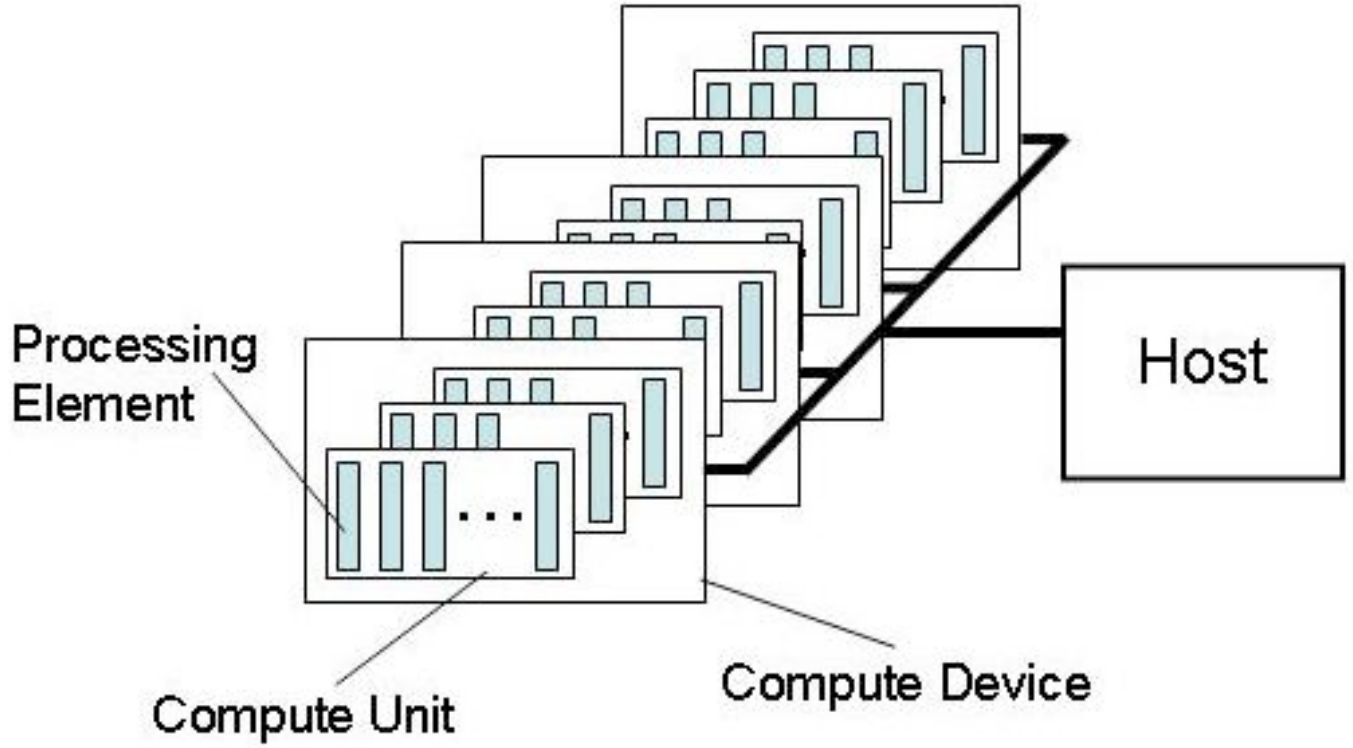
- OpenCL applications:
  - A host program running on the PC
  - One or more *Kernels* that are queued up to run on CPUs, GPUs, and "other processors".
- OpenCL is understood in terms of these models
  - Platform model
  - Execution model
  - Memory model
  - Programming model





OpenCL Platform model

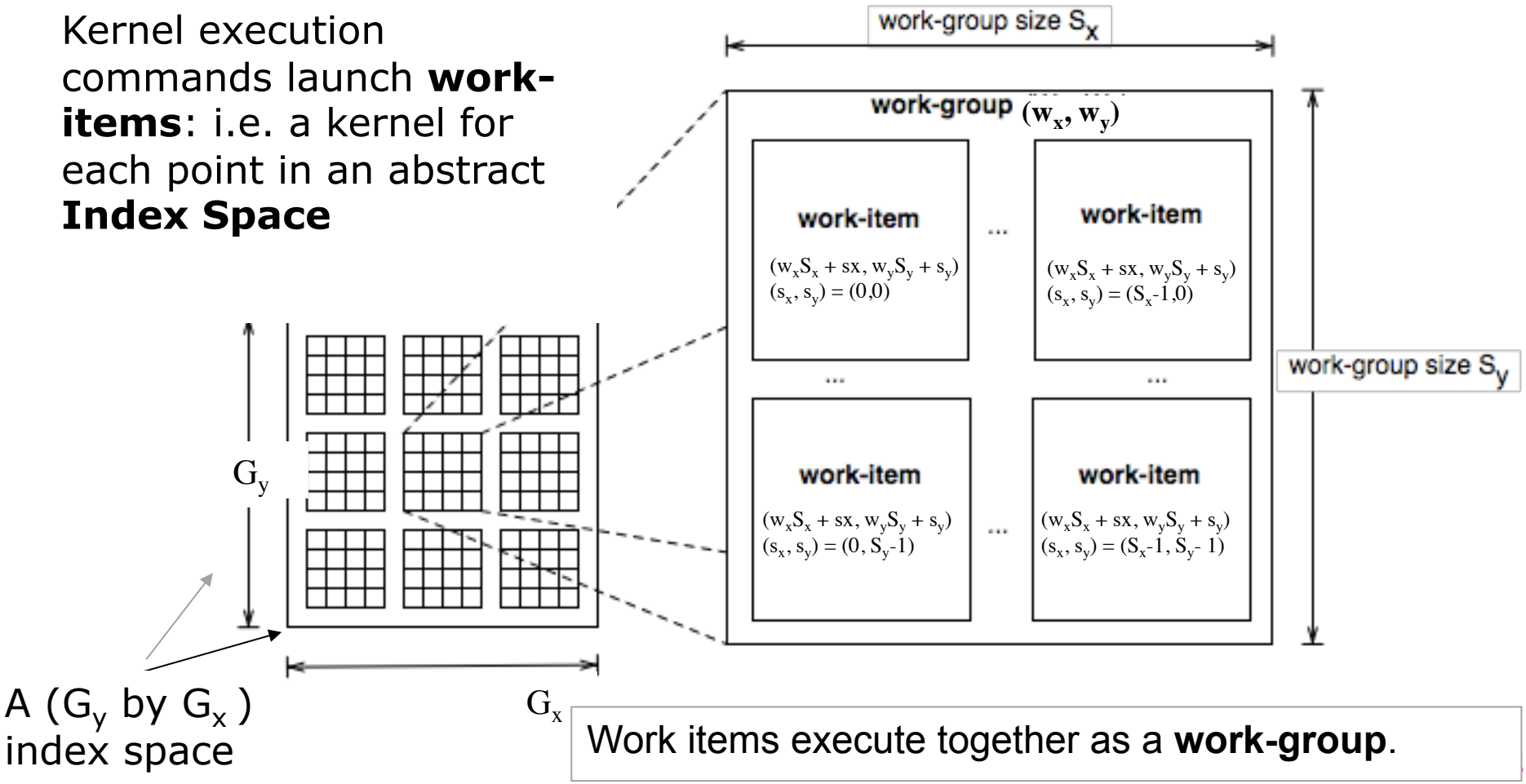
The basic platform is a host and one or more compute devices.



Execution Model

- Host defines a **command queue** and associates it with a context (devices, kernels, memory, etc).
- Host enqueues commands to the command queue

Kernel execution commands launch **work-items**: i.e. a kernel for each point in an abstract **Index Space**

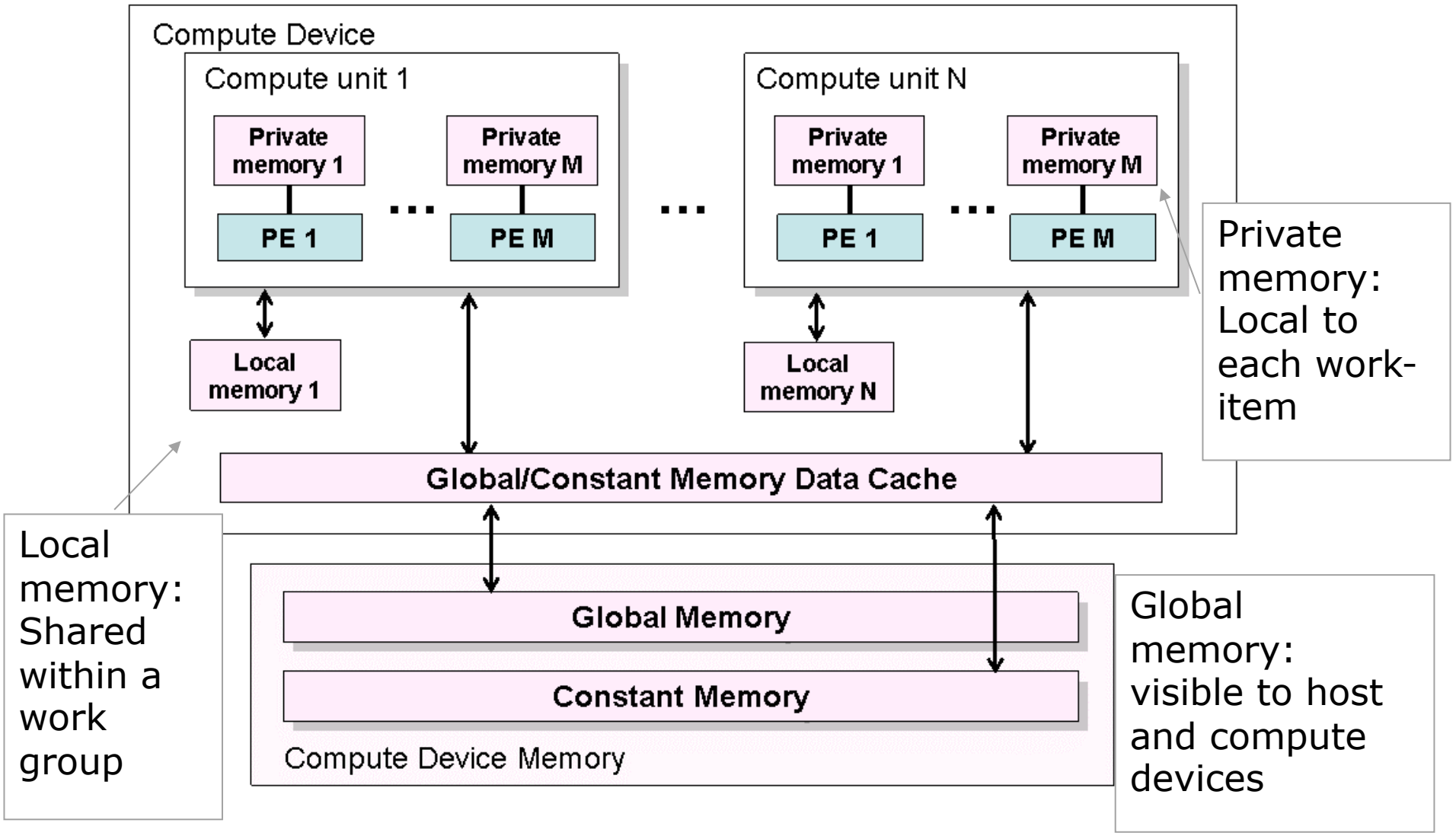


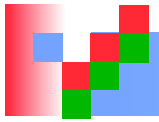
A (G_y by G_x) index space

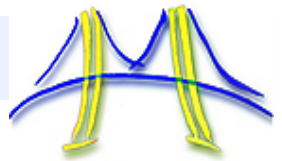
Work items execute together as a **work-group**.

OpenCL Memory model

- Implements a relaxed consistency, shared memory model

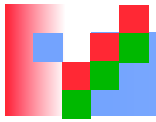




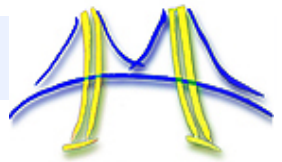


OpenCL programming model

- Data Parallel, SPMD
  - Work-items in a work-group run the same program
  - Update data structures in parallel using the work-item ID to select data and guide execution.
- Task Parallel
  - One work-item per work group … for coarse grained task-level parallelism.
  - Native function interface: trap-door to run arbitrary code from an OpenCL command-queue.

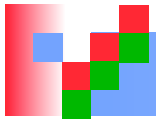


Programming Kernels: OpenCL C Language

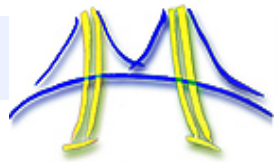


- Derived from ISO C99
  - No standard C99 headers, function pointers, recursion, variable length arrays, and bit fields
- Additions to the language for parallelism
  - Work-items and workgroups
  - Vector types
  - Synchronization
- Address space qualifiers
- Optimized image access
- Built-in functions

Acknowledgement: Aaftab Munshi of Apple

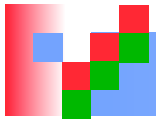


OpenCL C: Data Types

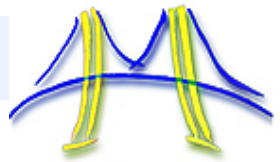


- Scalar data types
  - char , uchar, short, ushort, int, uint, long, ulong
  - bool, intptr_t, ptrdiff_t, size_t, uintptr_t, void, half (storage)
- Image types
  - image2d_t, image3d_t, sampler_t
- Vector data types

Acknowledgement: Aaftab Munshi of Apple



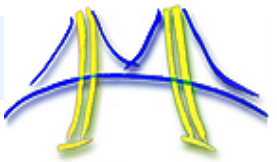
OpenCL C: Vector Types



- Portable
- Vector length of 2, 4, 8, and 16
- char2, ushort4, int8, float16, …
- Endian safe
- Aligned at vector length
- Vector operations and built-in functions

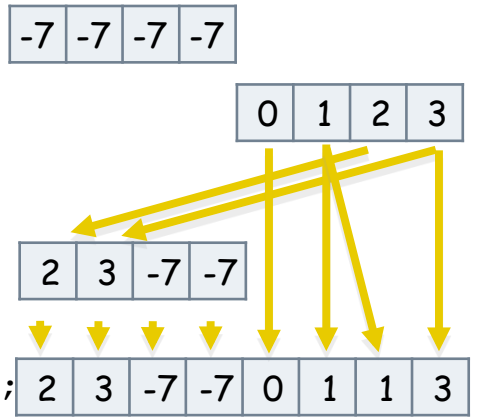
Acknowledgement: Aaftab Munshi of Apple

Vector Operations



- Vector literal

```
int4 vi0 = (int4) -7;
int4 vi1 = (int4)(0, 1, 2, 3);
```

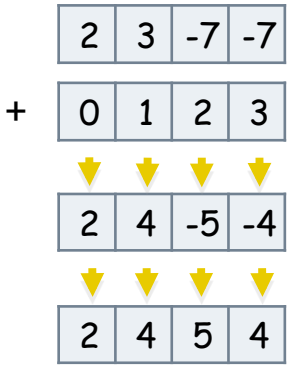


- Vector components

```
vi0.lo = vi1.hi;

int8 v8 = (int8)(vi0, vi1.s01, vi1.odd);
```

- Vector ops

```
vi0 += vi1;
```

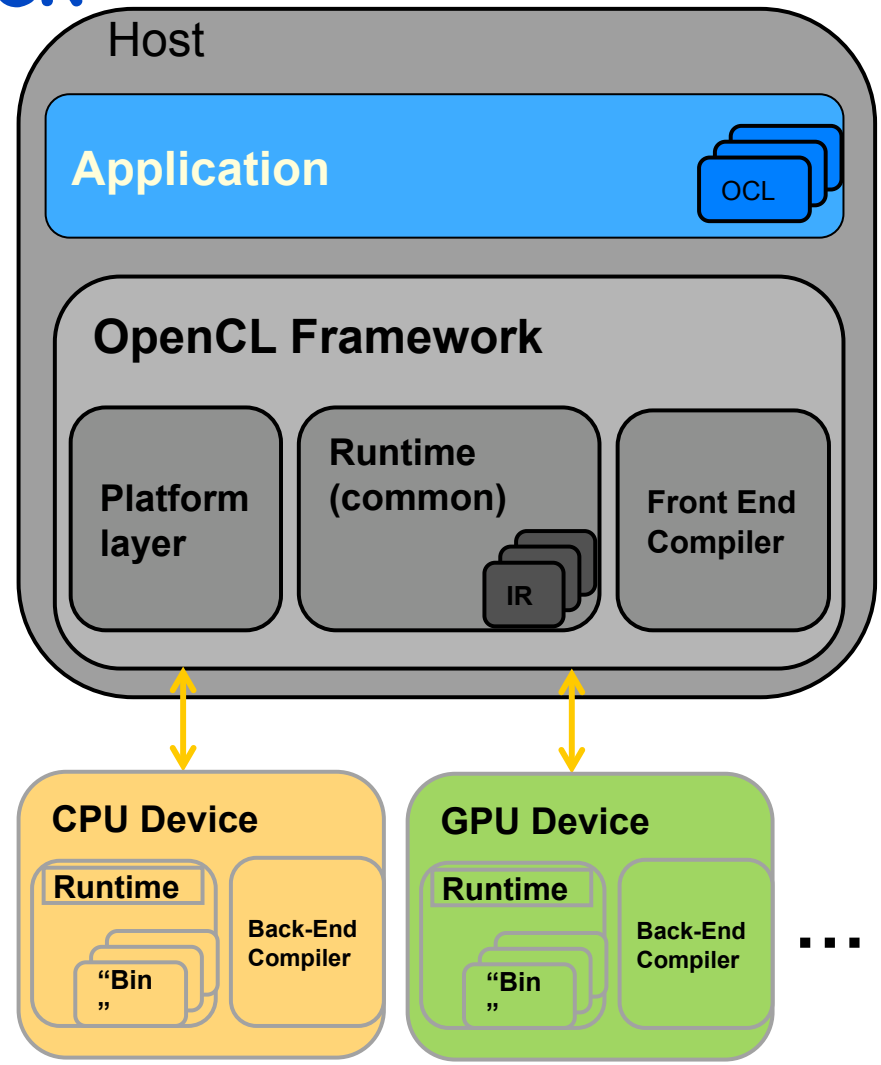


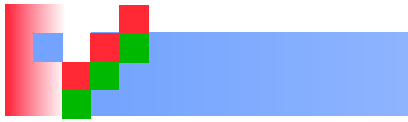

```
vi0 = abs(vi0);
```

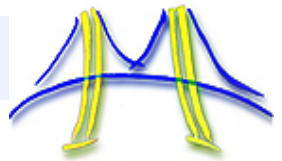
Acknowledgement: Aaftab Munshi of Apple

OpenCL Software Stack

- Platform Layer:
  - query and select compute devices
  - create contexts and command-queues
- Runtime
  - Coordinate between host and Compute devices
  - resource management
  - execute kernels
- Compiler
  - Implements kernel code on Target Device
  - ISO C99 subset + a few language additions
  - Builds executables online or offline





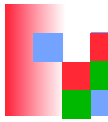


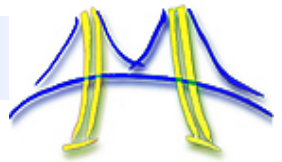
Example: vector addition

- The "hello world" program of data parallel programming is a program to add two vectors

  C[i] = A[i] + B[i] for i=1 to N

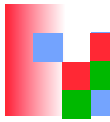
- For the OpenCl solution, there are two parts
  - Kernel code
  - Host code



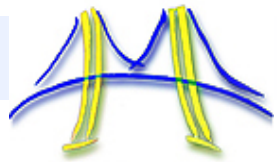


Vector Addition - Kernel

```
__kernel void vec_add (__global const float *a,
                       __global const float *b,
                       __global       float *c)
 {
     int gid = get_global_id(0);
     c[gid] = a[gid] + b[gid];
}
```



Vector Addition - Host Program

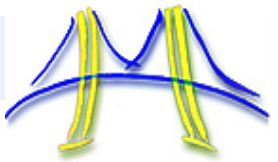


```
// create the OpenCL context on a GPU device
cl_context = clCreateContextFromType(0,
   CL_DEVICE_TYPE_GPU, NULL, NULL, NULL);

// get the list of GPU devices associated with context
clGetContextInfo(context, CL_CONTEXT_DEVICES, 0,
                                        NULL, &cb);
devices = malloc(cb);
clGetContextInfo(context, CL_CONTEXT_DEVICES, cb,
   devices, NULL);

// create a command-queue
cmd_queue = clCreateCommandQueue(context, devices[0],
   0, NULL);

// allocate the buffer memory objects
memobjs[0] = clCreateBuffer(context, CL_MEM_READ_ONLY |
   CL_MEM_COPY_HOST_PTR, sizeof(cl_float)*n, srcA,
                                        NULL);}
memobjs[1] = clCreateBuffer(context,CL_MEM_READ_ONLY |
   CL_MEM_COPY_HOST_PTR, sizeof(cl_float)*n, srcB,
                                        NULL);
memobjs[2] = clCreateBuffer(context,CL_MEM_WRITE_ONLY,
                          sizeof(cl_float)*n, NULL,
                                        NULL);
// create the program
program = clCreateProgramWithSource(context, 1,
   &program_source, NULL, NULL);
```

```
// build the program
err = clBuildProgram(program, 0, NULL, NULL, NULL,
                                                NULL);

// create the kernel
kernel = clCreateKernel(program, "vec_add", NULL);

// set the args values
err  = clSetKernelArg(kernel, 0, (void *) &memobjs[0],
                                  sizeof(cl_mem));
err |= clSetKernelArg(kernel, 1, (void *)&memobjs[1],
                                  sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *)&memobjs[2],
                                   sizeof(cl_mem));
// set work-item dimensions
global_work_size[0] = n;

// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel, 1,
   NULL, global_work_size, NULL, 0, NULL, NULL);

// read output array
err = clEnqueueReadBuffer(context, memobjs[2], CL_TRUE,
   0, n*sizeof(cl_float), dst, 0, NULL, NULL);
```

The host program is ugly … but its not too hard to understand (details with readable font in back-up slides)

Vector Addition - Host Program



Define platform and queues

```
// create the OpenCL context on a GPU device
cl_context = clCreateContextFromType(0,
clGetContextInfo(context, CL_CONTEXT_DEVICES, 0,
                                        NULL, &cb);
devices = malloc(cb);
clGetContextInfo(context, CL_CONTEXT_DEVICES, cb,
   devices, NULL);

// create a command-queue
cmd_queue = clCreateCommandQueue(context, devices[0],
   0, NULL);
```

Define Memory objects

```
memobjs[1] = clCreateBuffer(context,CL_MEM_READ_ONLY |
   CL_MEM_COPY_HOST_PTR, sizeof(cl_float)*n, srcB,
   NULL);
memobjs[2] = clCreateBuffer(context,CL_MEM_WRITE_ONLY,
                            sizeof(cl_float)*n, NULL,
   NULL);
```

Create the program

```
// create the program
program = clCreateProgramWithSource(context, 1,
```

Build the program

```
err = clBuildProgram(program, 0, NULL, NULL, NULL,
   NULL);
```

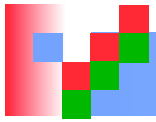
Create and setup kernel

```
// set the args values
err  = clSetKernelArg(kernel, 0, (void *) &memobjs[0],
                                 sizeof(cl_mem));
err |= clSetKernelArg(kernel, 1, (void *)&memobjs[1],
                                 sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *)&memobjs[2],
                                  sizeof(cl_mem));
```

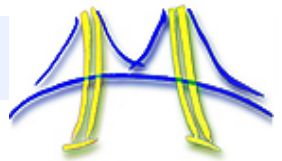
Execute the kernel

```
// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel, 1,
   NULL, global_work_size, NULL, 0, NULL, NULL);
```

Read results on the host



Agenda



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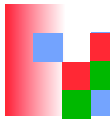
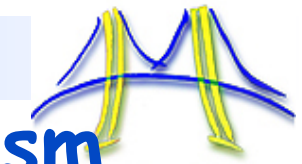




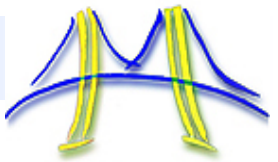
OpenCL's Two Styles of Data-Parallelism

- Explicit SIMD data parallelism:
  - The kernel defines one stream of instructions
  - Parallelism from using wide vector types
  - Size vector types to match native HW width
  - Combine with task parallelism to exploit multiple cores.

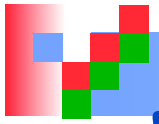
- Implicit SIMD data parallelism (i.e. shader-style):
  - Write the kernel as a "scalar program"
  - Use vector data types sized naturally to the algorithm
  - Kernel automatically mapped to SIMD-compute-resources and cores by the compiler/runtime/hardware.

Both approaches are viable CPU options

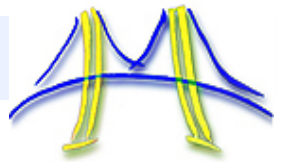
Data-Parallelism: options on IA processors



- Explicit SIMD data parallelism
  - Programmer chooses vector data type (width)
  - Compiler hints using attributes
    - » vec_type_hint(type*n*)
- Implicit SIMD Data parallel
  - Map onto CPUs, GPUs, Larrabee, …
    - » SSE/AVX/LRBni: 4/8/16 workitems in parallel
- Hybrid use of the two methods
    - » AVX: can run two 4-wide workitems in parallel
    - » LRBni: can run four 4-wide workitems in parallel



Explicit SIMD data parallelism



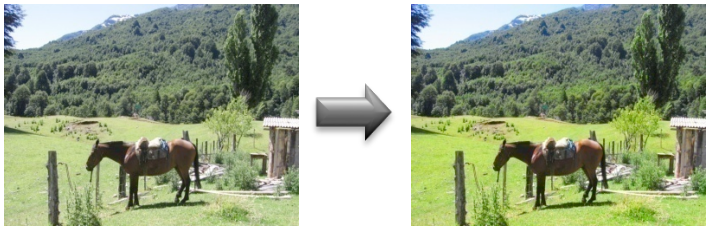
- OpenCL as a portable interface to vector instruction sets.
  - Block loops and pack data into vector types (float4, ushort16, etc).
  - Replace scalar ops in loops with blocked loops and vector ops.
  - Unroll loops, optimize indexing to match machine vector width

```
float a[N], b[N], c[N];
for (i=0; i<N; i++)
    c[i] = a[i]*b[i];
<<< the above becomes >>>>
float4 a[N/4], b[N/4], c[N/4];
for (i=0; i<N/4; i++)
     c[i] = a[i]*b[i];
```

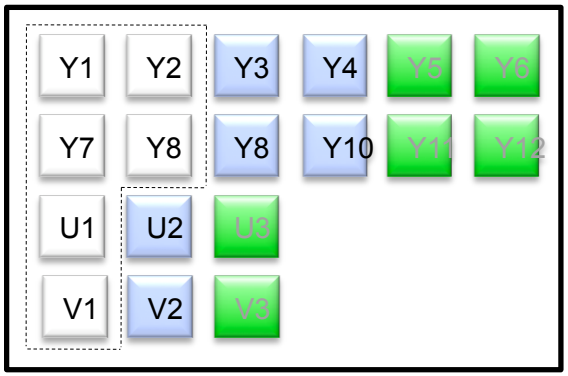
Explicit SIMD data parallelism means you tune your code to the vector width and other properties of the compute device

Video Processing Case Study

- 2 algorithms from the Video Processing domain
  - Color Enhancement
    - » Enhance the saturation (color strength) of individual colors
      - Red, Green, Blue, Yellow, Cyan and Magenta
  - Contrast Enhancement
    - » Improve extreme dark and bright images



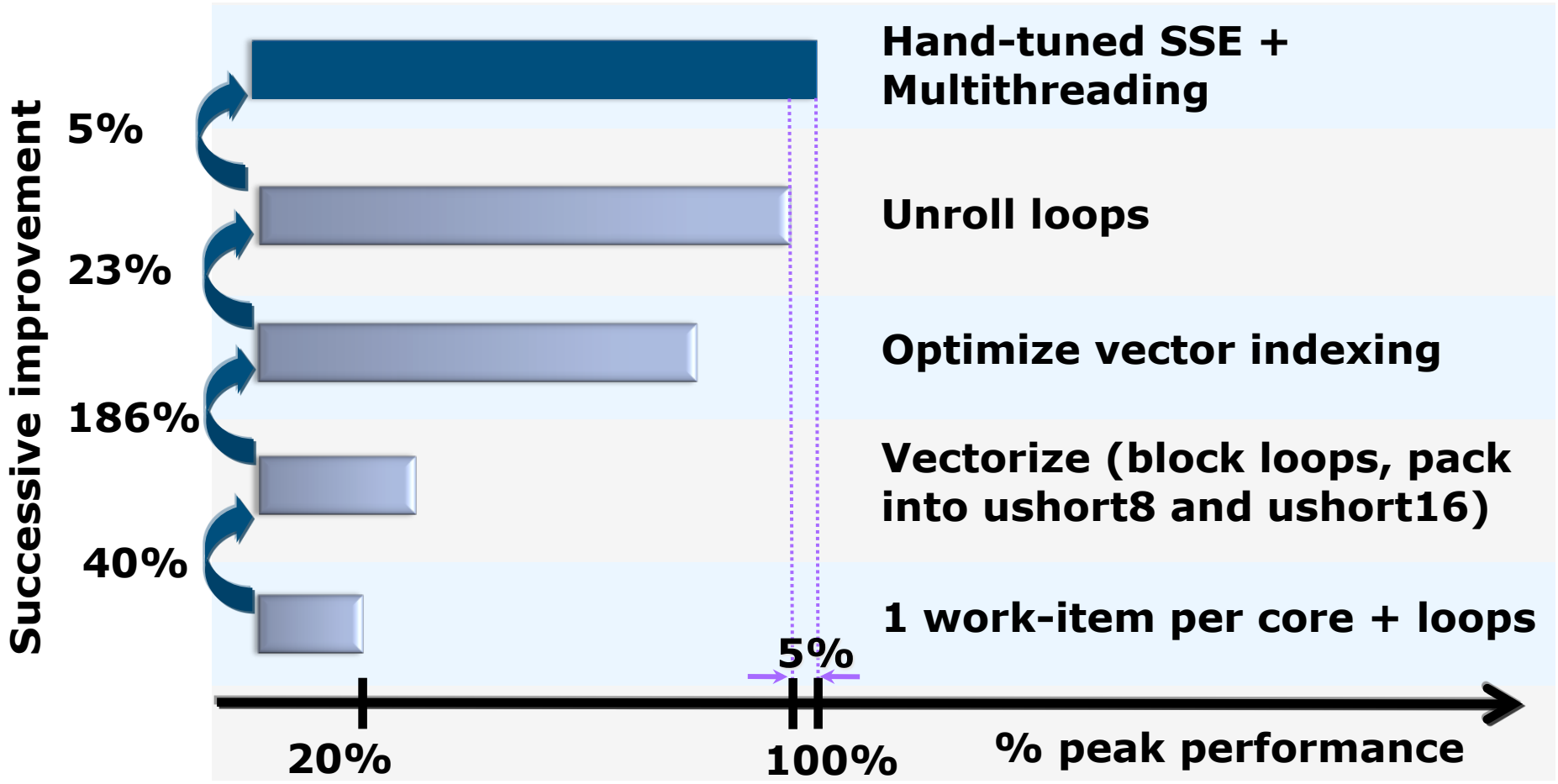
- Video Frames
  - Processed in YUV 4:2:0 planar color space
  - 10 bits per color component
    - » Contained in *ushort* (unsigned short)
  - Fixed point arithmetic
  - Structure of arrays (SOA)



YUV 4:2:0 Frame

Explicit SIMD data parallelism: Case Study

- Video contrast/color optimization kernel on a dual core CPU.

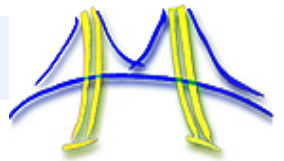


Good news: OpenCL code 95% of hand-tuned SSE/MT perf.
Bad news: New platform, redo all those optimizations.

3 Ghz dual core CPU
pre-release version of OpenCL
Source: Intel Corp.

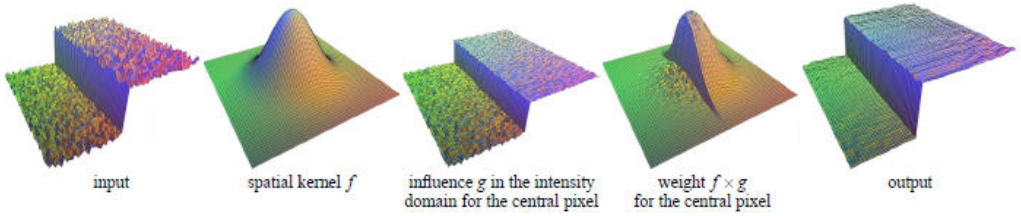
* Results have been estimated based on internal Intel analysis and are provided for informational purposes only. Any difference in system hardware or software design or configuration may affect actual performance.

Towards "Portable" Performance

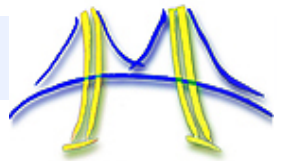


- The following C code is an example of a Bilateral 1D filter:
- Reminder: Bilateral filter is an edge preserving image processing algorithm.
- See more information here: http://scien.stanford.edu/class/psych221/projects/06/imagescaling/bilati.html

```
void P4_Bilateral9 (int start, int end, float v)
{
   int i, j, k;
   float w[4], a[4], p[4];
   float inv_of_2v = -0.5 / v;
   for (i = start; i < end; i++) {
      float wt[4] = { 1.0f, 1.0f, 1.0f, 1.0f };
      for (k = 0; k < 4; k++)
         a[k] = image[i][k];
      for (j = 1; j <= 4; j++) {
         for (k = 0; k < 4; k++)
            p[k] = image[i - j*SIZE][k] - image[i][k];
         for (k = 0; k < 4; k++)
            w[k] = exp (p[k] * p[k] * inv_of_2v);
         for (k = 0; k < 4; k++) {
            wt[k] += w[k];
            a[k] += w[k] * image[i - j*SIZE][k];
         }
      }
      for (j = 1; j <= 4; j++) {
         for (k = 0; k < 4; k++)
            p[k] = image[i + j*SIZE][k] - image[i][k];
         for (k = 0; k < 4; k++;
            w[k] = exp (p[k] * p[k] * inv_of_2v);
         for (k = 0; k < 4; k++) {
            wt[k] += w[k];
            a[k] += w[k] * image[i + j*SIZE][k];
         }
      }
      for (k = 0; k < 4; k++) {
         image2[i][k] = a[k] / wt[k];
      }
   }
}
```



Towards "Portable" Performance



- The foll
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- Reminde
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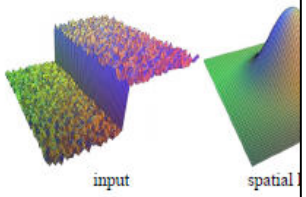
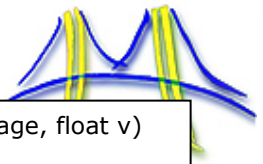
- See mor
  http://sci
  psych221/
  bilati.htm

```
void P4_Bilateral9 (int start, int end, float v)
{
    <<< Declarations >>>
    for (i = start; i < end; i++) {
        for (j = 1; j <= 4; j++) {
        <<< a series of short loops >>>>
         }
        for (j = 1; j <= 4; j++) {
         <<< a 2nd series of short loops >>>
        }
    }
}
```



"Implicit SIMD" data parallel code

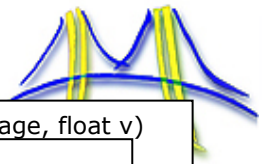


- "outer" loop replaced by work-items running over an NDRange index set.
- NDRange 4*image size … since each workitem does a color for each pixel.
- Leave it to the compiler to map work-items onto lanes of the vector units …

```
__kernel void P4_Bilateral9 (__global float* inImage, __global float* outImage, float v)
{
    const size_t myID     = get_global_id(0);
    const float inv_of_2v = -0.5f / v;
    const size_t myRow    = myID / IMAGE_WIDTH;
          size_t maxDistance = min(DISTANCE, myRow);
           maxDistance = min(maxDistance, IMAGE_HEIGHT - myRow);
    float currentPixel, neighborPixel, newPixel;
    float diff;
    float accumulatedWeights, currentWeights;
    newPixel = currentPixel = inImage[myID];
    accumulatedWeights = 1.0f;
    for (size_t dist = 1; dist <= maxDistance; ++dist)
    {
          neighborPixel          = inImage[myID + dist*IMAGE_WIDTH];
          diff                   = neighborPixel - currentPixel;
          currentWeights         = exp(diff * diff * inv_of_2v);
          accumulatedWeights += currentWeights;
          newPixel               += neighborPixel * currentWeights;
          neighborPixel            = inImage[myID - dist*IMAGE_WIDTH];
          diff                     = neighborPixel - currentPixel;
          currentWeights           = exp(diff * diff * inv_of_2v);
          accumulatedWeights += currentWeights;
          newPixel               + = neighborPixel * currentWeights;
    }
    outImage[myID] = newPixel / accumulatedWeights;
}
```

Source: Intel Corp.

"Implicit SIMD" data parallel code



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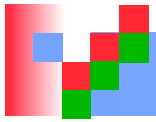
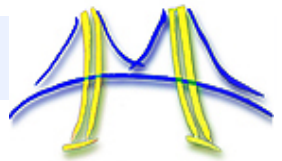
  …

__kernel void P4_Bilateral9 (__global float* inImage, __global float* outImage, float v)

```
__kernel void p4_bilateral9(__global float* inImage,
                            __global float* outImage, float v)
{
    const size_t myID     = get_global_id(0);
    <<< declarations >>>
    for (size_t dist = 1; dist <= maxDistance; ++dist){
        neighborPixel     = inImage[myID +
                                    dist*IMAGE_WIDTH];
        diff              = neighborPixel - currentPixel;
        currentWeights    = exp(diff * diff * inv_of_2v);
      << plus others to compute pixels, weights, etc >>
        accumulatedWeights += currentWeights;
    }
    outImage[myID] = newPixel / accumulatedWeights;
}
```

Source: Intel Corp.

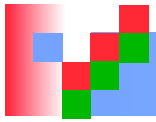


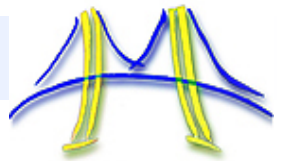


Portable Performance in OpenCL

- Implicit SIMD code … where the framework maps work-items onto the "lanes of the vector unit" … creates the opportunity for portable code that performs well on full range of OpenCL compute devices.

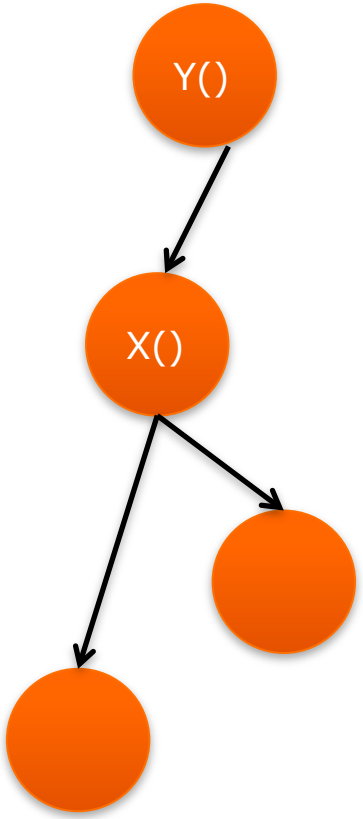
- Requires mature OpenCL technology that "knows" how to do this:
  - … But it is important to note …. we know this approach works since its based on the way shader compilers work today.



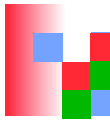


Task Parallelism Overview

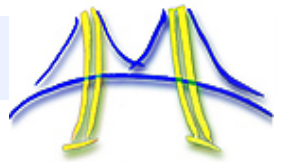
- Think of a task as an asynchronous function call
  - "Do X at some point in the future"
  - Optionally "… after Y is done"
  - Light weight, often in user space
- Strengths
  - Copes well with heterogeneous workloads
  - Doesn't require 1000's of strands
  - Scales well with core count
- Limitations
  - No automatic support for latency hiding
  - Must explicitly write SIMD code



A natural fit to multi-core CPUs



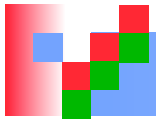
Task Parallelism in OpenCL

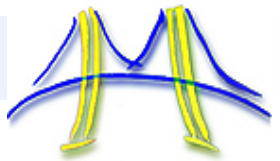


- clEnqueueTask
  - Imagine "sea of different tasks" executing concurrently
  - A task "owns the core" (i.e., a workgroup size of 1)

- Use tasks when algorithm…
  - Benefits from large amount of local/private memory
  - Has predictable global memory accesses
  - Can be programmed using explicit vector style
  - "Just doesn't have 1000's of identical things to do"

- Use data-parallel kernels when algorithm…
  - Does not benefit from large amounts of local/private memory
  - Has unpredictable global memory accesses
  - Needs to apply same operation across large number of data elements





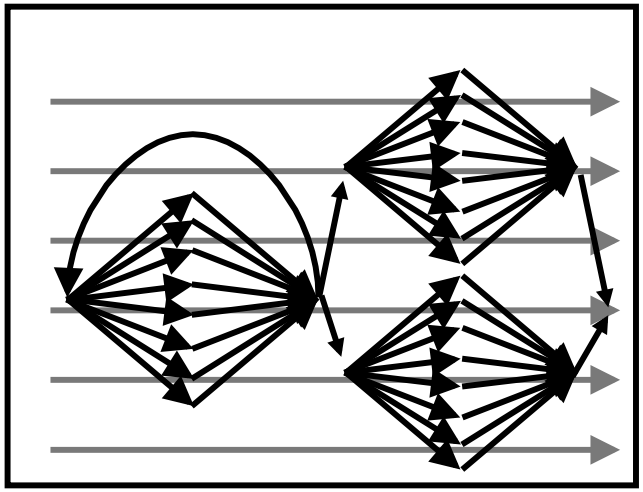
Future Parallel Programming

- Real world applications contain data parallel parts as well as serial/sequential parts

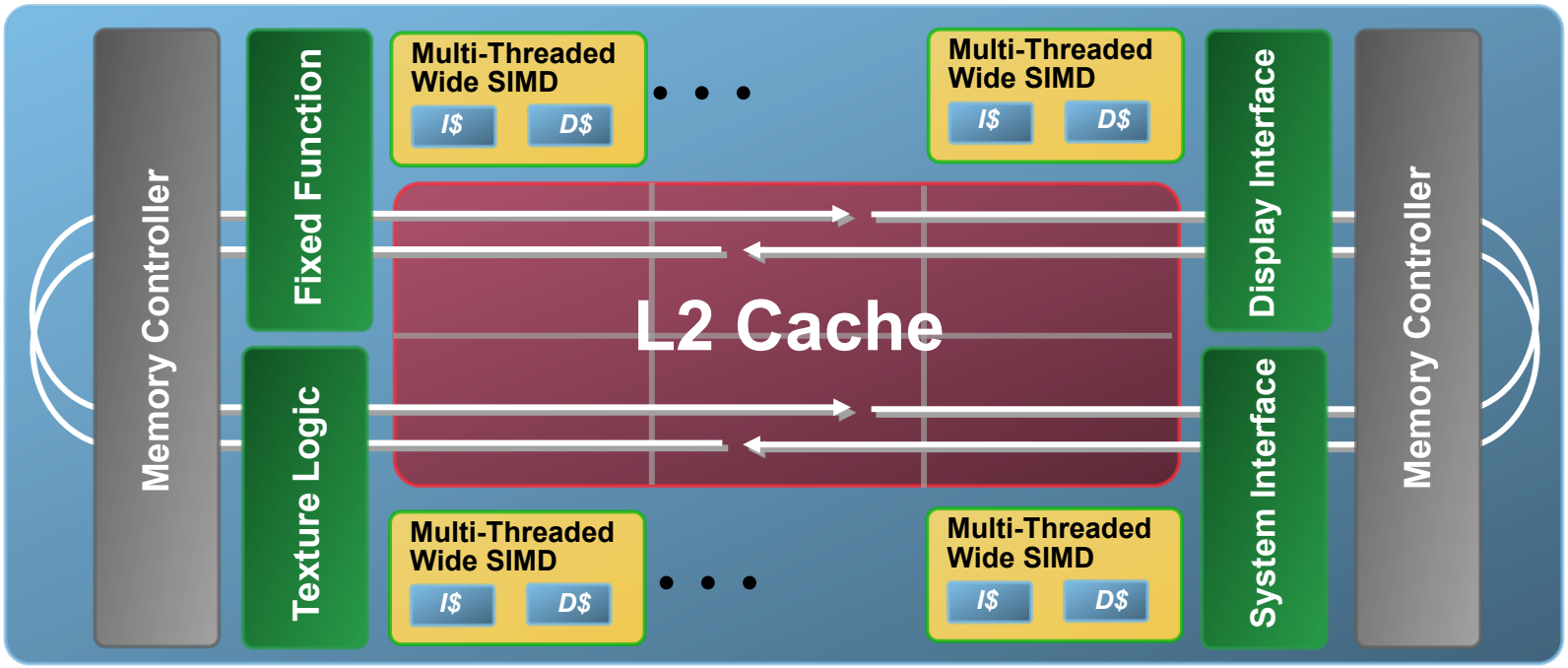
- OpenCL addresses these Apps need by supporting Data Parallel & Task Parallel

- "Braided Parallelism" – composing Data Parallel & Task Parallel constructs in a single algorithm

- CPUs are ideal for Braided Parallelism

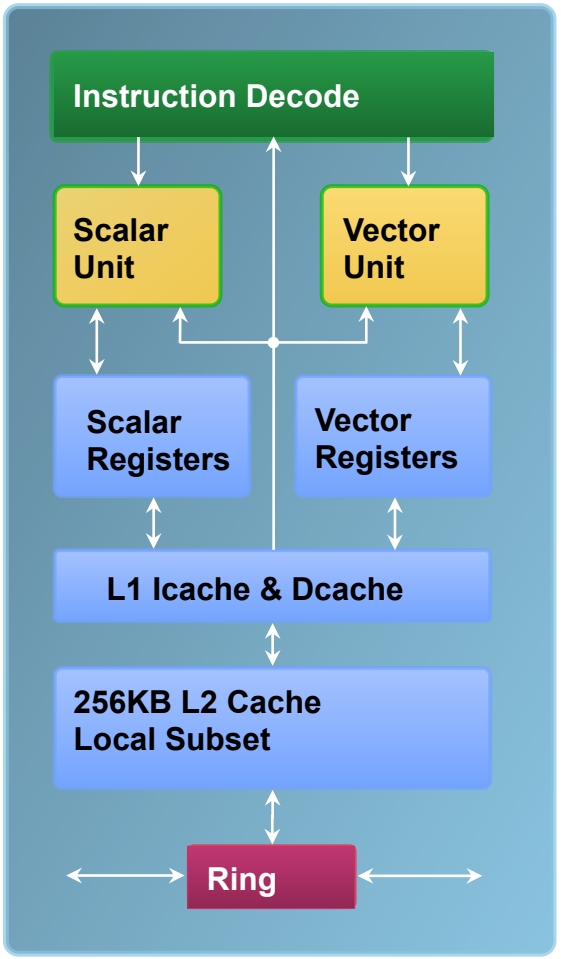


Future parallel programming: Larrabee

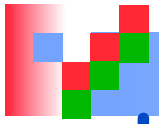


- Cores communicate on a wide ring bus
  - Fast access to memory and fixed function blocks
  - Fast access for cache coherency
- L2 cache is partitioned among the cores
  - Provides high aggregate bandwidth
  - Allows data replication & sharing

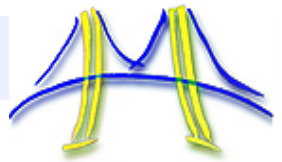
Processor Core Block Diagram



- Separate scalar and vector units with separate registers
- Vector unit: 16 32-bit ops/clock
- In-order instruction execution
- Short execution pipelines
- Fast access from L1 cache
- Direct connection to each core's subset of the L2 cache
- Prefetch instructions load L1 and L2 caches

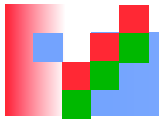


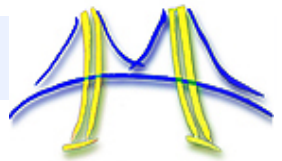
Key Differences from Typical GPUs



- Each Larrabee core is a complete Intel processor
  - Context switching & pre-emptive multi-tasking
  - Virtual memory and page swapping, even in texture logic
  - Fully coherent caches at all levels of the hierarchy
- Efficient inter-block communication
  - Ring bus for full inter-processor communication
  - Low latency high bandwidth L1 and L2 caches
  - Fast synchronization between cores and caches

Larrabee is perfect for the braided parallelism in future applications



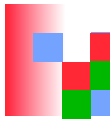


Conclusion

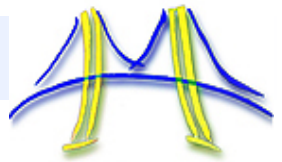
- OpenCL defines a platform-API/framework for heterogeneous computing … not just GPGPU or CPU-offload programming.

- OpenCL has the potential to deliver portably performant code; but only if its used correctly:
  - Implicit SIMD data parallel code has the best chance of mapping onto a diverse range of hardware … once OpenCL implementation quality catches up with mature shader languages.

- The future is clear:
  - Parallelism mixing task parallel and data parallel code in a single program … balancing the load among ALL OF the platform's available resources.
  - OpenCL can handle this … and emerging platforms ~~(e.g Larrabee)~~ will increasingly emphasize this model.



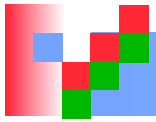
References

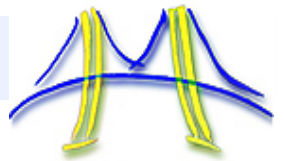


- **s09.idav.ucdavis.edu** for slides from a Siggraph2009 course titled "Beyond Programmable Shading"

- Seiler, L., Carmean, D., et al. 2008. *Larrabee: A many-core x86 architecture for visual computing*. SIGGRAPH '08: ACM SIGGRAPH 2008 Papers, ACM Press, New York, NY

- Fatahalian, K., Houston, M., "GPUs: a closer look", Communications of the ACM October 2008, vol 51 #10. graphics.stanford.edu/~kayvonf/papers/fatahalianCACM.pdf

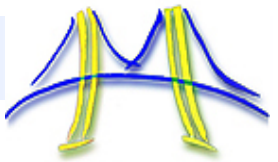




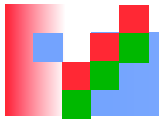
Agenda

- Ugly programming models and why they rule
- The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- An OpenCL "deep dive"

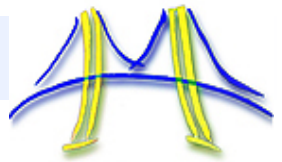
Basic OpenCL Program Structure



- Host program
  - Query compute devices
  - Create contexts
  - Create memory objects associated to contexts
  - Compile and create kernel program objects
  - Issue commands to command-queue
  - Synchronization of commands
  - Clean up OpenCL resources
- Kernels
  - C code with some restrictions and extensions

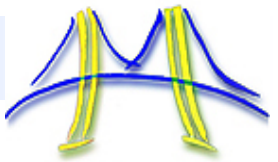


Example: Vector Addition



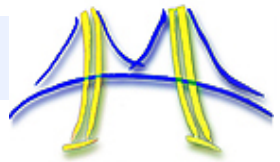
- Compute c = a + b
  - a, b, and c are vectors of length *N*
- Basic OpenCL concepts
  - Simple kernel code
  - Basic context management
  - Memory allocation
  - Kernel invocation

Platform Layer: Basic discovery

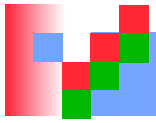


- Platform layer allows applications to query for platform specific features
- Querying platform info Querying devices
  - *clGetDeviceIDs*()
    - » Find out what compute devices are on the system
    - » Device types include CPUs, GPUs, or Accelerators
  - *clGetDeviceInfo*()
    - » Queries the capabilities of the discovered compute devices such as:
      - Number of compute cores
      - Maximum work-item and work-group size
      - Sizes of the different memory spaces
      - Maximum memory object size

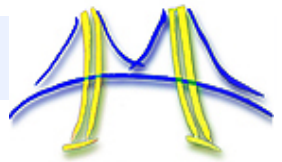
Platform Layer: Contexts



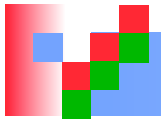
- Creating contexts
  - Contexts are used by the OpenCL runtime to manage objects and execute kernels on one or more devices
  - Contexts are associated to one or more devices
    - » Multiple contexts could be associated to the same device
  - *clCreateContext*() and *clCreateContextFromType*() returns a *handle* to the created contexts



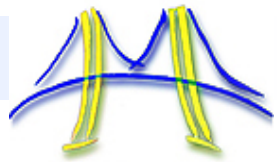
Platform layer: Command-Queues



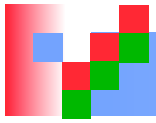
- Command-queues store a set of operations to perform
- Command-queues are associated to a context
- Multiple command-queues can be created to handle independent commands that don't require synchronization
- Execution of the command-queue is guaranteed to be completed at sync points



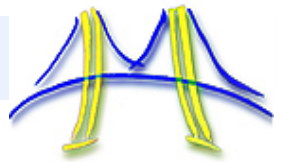
VecAdd: Context, Devices, Queue



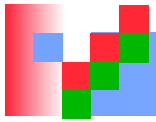
```
// create the OpenCL context on a GPU device
cl_context context = clCreateContextFromType(0, // (must be 0)
                        CL_DEVICE_TYPE_GPU,
                        NULL,  // error callback
                        NULL,  // user data
                        NULL); // error code

// get the list of GPU devices associated with context
size_t cb;
clGetContextInfo(context, CL_CONTEXT_DEVICES, 0, NULL, &cb);
cl_device_id *devices = malloc(cb);
clGetContextInfo(context, CL_CONTEXT_DEVICES, cb, devices, NULL);

// create a command-queue
cl_cmd_queue cmd_queue = clCreateCommandQueue(context,
            devices[0],  0,     // default options
                        NULL); // error code
```



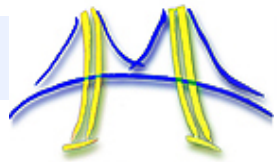
Memory Objects



- Buffer objects
  - One-dimensional collection of objects (like C arrays)
  - Valid elements include scalar and vector types as well as user defined structures
  - Buffer objects can be accessed via pointers in the kernel
- Image objects
  - Two- or three-dimensional texture, frame-buffer, or images
  - Must be addressed through built-in functions
- Sampler objects
  - Describes how to sample an image in the kernel
    - » Addressing modes
    - » Filtering modes

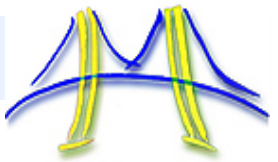


Creating Memory Objects



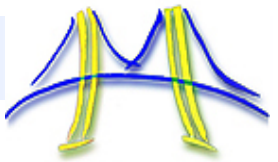
- *clCreateBuffer()*, *clCreateImage2D*(), and *clCreateImage3D*()
- Memory objects are created with an associated context
- Memory can be created as read only, write only, or read-write
- Where objects are created in the platform memory space can be controlled
  - Device memory
  - Device memory with data copied from a host pointer
  - Host memory
  - Host memory associated with a pointer
    - » Memory at that pointer is guaranteed to be valid at synchronization points

Manipulating Object Data

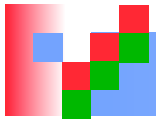


- Object data can be copied to host memory, from host memory, or to other objects
- Memory commands are enqueued in the command buffer and processed when the command is executed
  - *clEnqueueReadBuffer*(), *clEnqueueReadImage*()
  - *clEnqueueWriteBuffer*(), *clEnqueueWriteImage*()
  - *clEnqueueCopyBuffer*(), *clEnqueueCopyImage*()
- Data can be copied between Image and Buffer objects
  - *clEnqueueCopyImageToBuffer*()
  - *clEnqueueCopyBufferToImage*()
- Regions of the object data can be accessed by mapping into the host address space
  - *clEnqueueMapBuffer*(), *clEnqueueMapImage*()
  - *clEnqueueUnmapMemObject*()

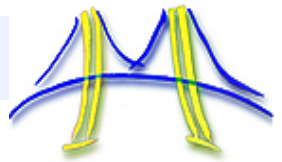
VecAdd: Create Memory Objects



```
cl_mem memobjs[3];
// allocate input buffer memory objects
memobjs[0] = clCreateBuffer(context,
                    CL_MEM_READ_ONLY |    // flags
                    CL_MEM_COPY_HOST_PTR,
                    sizeof(cl_float)*n,   // size
                    srcA,                 // host pointer
                    NULL);                // error code
memobjs[1] = clCreateBuffer(context,
             CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
             sizeof(cl_float)*n, srcB, NULL);

// allocate input buffer memory object
memobjs[2] = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                            sizeof(cl_float)*n, NULL, NULL);
```

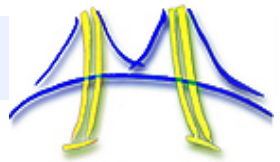


Program Objects



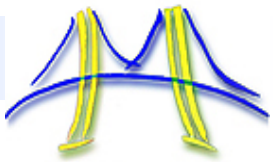
- Program objects encapsulate:
  - An associated context
  - Program source or binary
  - list of targeted devices, build options
  - Number of attached kernel objects
- Build process
  1. Create program object
     - » clCreateProgramWithSource()
     - » clCreateProgramWithBinary()
  2. Build program executable
     - » Compile and link from source or binary for all devices or specific devices in the associated context
     - » clBuildProgram()
     - » Build options
       - Preprocessor, float point behavior, optimizations, etc

Kernel Objects

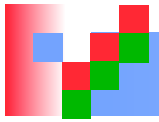


- Kernel objects encapsulate
  - Specific kernel functions declared in a program
  - Argument values used for kernel execution
- Creating kernel objects
  - *clCreateKernel*() - creates a kernel object for a single function in a program
- Setting arguments
  - *clSetKernelArg*(<kernel>, <argument index>)
  - Each argument data must be set for the kernel function
  - Argument values copied and stored in the kernel object
- Kernel vs. program objects
  - Kernels are related to program execution
  - Programs are related to program source

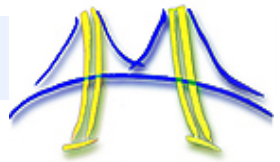
VecAdd: Program and Kernel



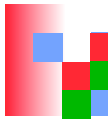
```
// create the program
cl_program program = clCreateProgramWithSource(
                context,
                1,                  // string count
                &program_source, // program strings
                NULL,               // string lengths
                NULL);              // error code
// build the program
cl_int err = clBuildProgram(program,
                0,      // num devices in device list
                NULL,   // device list
                NULL,   // options
                NULL,   // notifier callback function ptr
                NULL); // user data
// create the kernel
cl_kernel kernel = clCreateKernel(program, "vec_add", NULL);
```



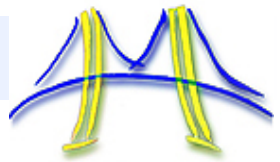
VecAdd: Set Kernel Arguments



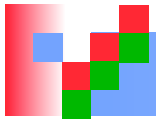
```
// set "a" vector argument
err  = clSetKernelArg(kernel,
                      0,                      // argument index
                      (void *)&memobjs[0], // argument data
                      sizeof(cl_mem));     // argument data size

// set "b" vector argument
err |= clSetKernelArg(kernel, 1, (void *)&memobjs[1],
                      sizeof(cl_mem));

// set "c" vector argument
err |= clSetKernelArg(kernel, 2, (void *)&memobjs[2],
                      sizeof(cl_mem));
```



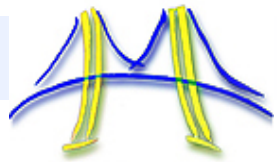
Kernel Execution



- A command to execute a kernel must be enqueued to the command-queue
- *clEnqueueNDRangeKernel*()
  - Data-parallel execution model
  - Describes the ***index space*** for kernel execution
  - Requires information on NDRange dimensions and work-group size
- *clEnqueueTask*()
  - Task-parallel execution model (multiple queued tasks)
  - Kernel is executed on a single work-item
- *clEnqueueNativeKernel*()
  - Task-parallel execution model
  - Executes a native C/C++ function not compiled using the OpenCL compiler
  - This mode does not use a kernel object so arguments must be passed in

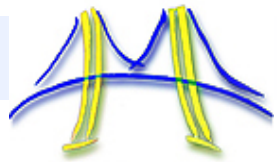


Command-Queues

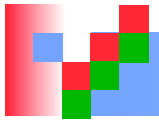


- Command-queue execution
  - Execution model signals when commands are complete or data is ready
  - Command-queue could be explicitly flushed to the device
  - Command-queues execute in-order or out-of-order
    - » In-order - commands complete in the order queued and correct memory is consistent
    - » Out-of-order - no guarantee when commands are executed or memory is consistent without synchronization

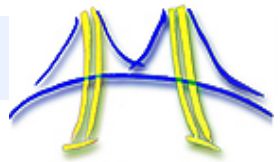
Synchronization



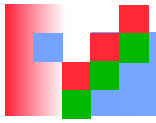
- Synchronization
  - Signals when commands are completed to the host or other commands in queue
  - Blocking calls
    - » Commands that do not return until complete
    - » clEnqueueReadBuffer() can be called as blocking and will block until complete
  - *Event objects*
    - » Tracks execution status of a command
    - » Some commands can be blocked until event objects signal a completion of previous command
      - clEnqueueNDRangeKernel() can take an event object as an argument and wait until a previous command (e.g., clEnqueueWriteBuffer) is complete
  - Queue barriers - queued commands that can block command execution



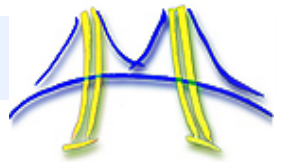
VecAdd: Invoke Kernel, Read Output



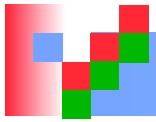
```
size_t global_work_size[1] = n; // set work-item dimensions
// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel,
                      1,          // Work dimensions
                      NULL,       // must be NULL (work offset)
                      global_work_size,
                      NULL,       // automatic local work size
                      0,          // no events to wait on
                      NULL,       // event list
                      NULL);      // event for this kernel
// read output array
err = clEnqueueReadBuffer( context, memobjs[2],
                      CL_TRUE,              // blocking
                      0,                    // offset
                      n*sizeof(cl_float), // size
                      dst,                  // pointer
                      0, NULL, NULL);       // events
```



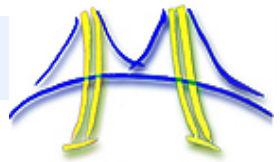
OpenCL C for Compute Kernels



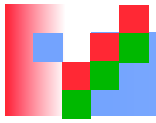
- Derived from ISO C99
  - A few restrictions: recursion, function pointers, functions in C99 standard headers ...
  - Preprocessing directives defined by C99 are supported
- Built-in Data Types
  - Scalar and vector data types, Pointers
  - Data-type conversion functions: convert_type<_sat><_roundingmode>
  - Image types: image2d_t, image3d_t and sampler_t
- Built-in Functions — Required
  - work-item functions, math.h, read and write image
  - Relational, geometric functions, synchronization functions
- Built-in Functions — Optional
  - double precision, atomics to global and local memory
  - selection of rounding mode, writes to image3d_t surface



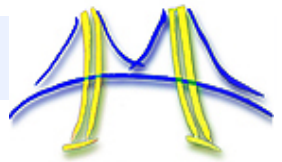
OpenCL C Language Highlights



- Function qualifiers
  - "__kernel" qualifier declares a function as a kernel
  - Kernels can call other kernel functions
- Address space qualifiers
  - __global, __local, __constant, __private
  - Pointer kernel arguments must be declared with an address space qualifier
- Work-item functions
  - Query work-item identifiers
    - » get_work_dim(), get_global_id(), get_local_id(), get_group_id()
- Synchronization functions
  - Barriers - all work-items within a work-group must execute the barrier function before any work-item can continue
  - Memory fences - provides ordering between memory operations

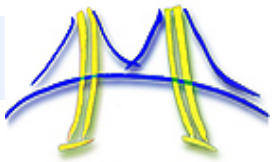


OpenCL C Language Restrictions



- Pointers to functions are not allowed
- Pointers to pointers allowed within a kernel, but not as an argument
- Bit-fields are not supported
- Variable length arrays and structures are not supported
- Recursion is not supported
- Writes to a pointer of types less than 32-bit are not supported
- Double types are not supported, but reserved

Vector Addition Kernel



```
__kernel void vec_add (__global const float *a,
                       __global const float *b,
                       __global       float *c)
{
    int gid = get_global_id(0);
    c[gid] = a[gid] + b[gid];
}
```

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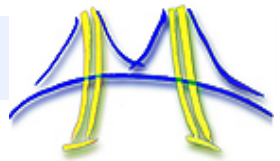

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