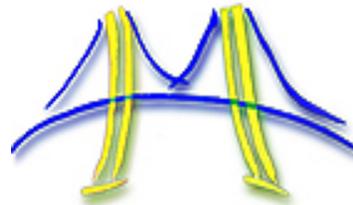


PARLab Parallel Boot Camp

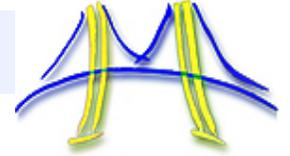
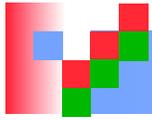


Introduction to OpenCL

Tim Mattson

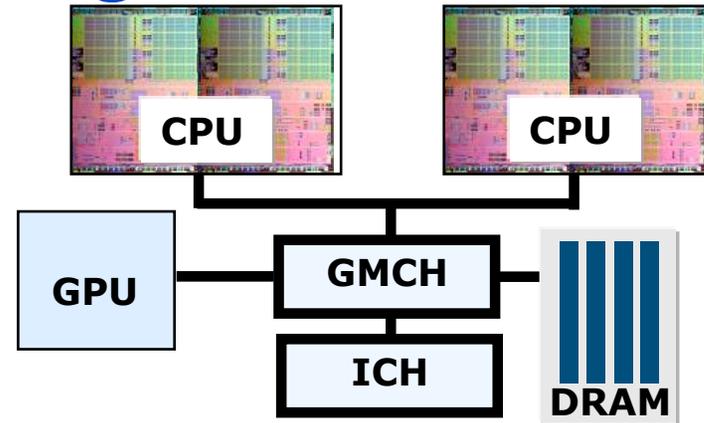
Microprocessor and Programming Research Lab

Intel Corp.

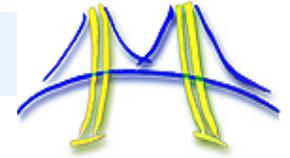
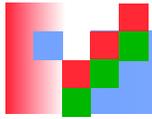


Heterogeneous computing

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

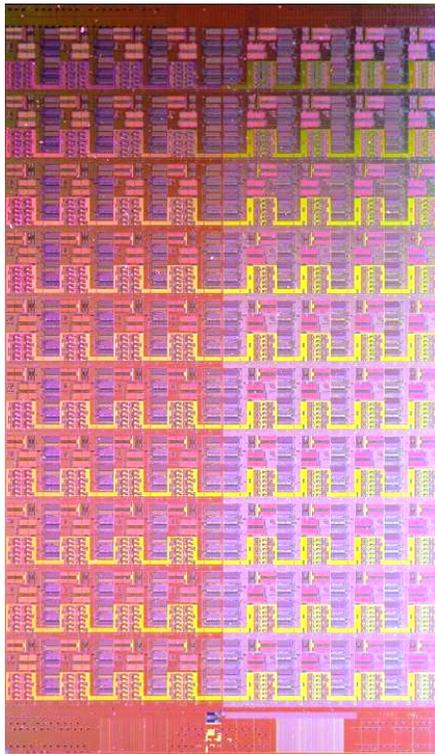


- The goal should NOT be to "off-load" the CPU. We need to make the best use of all the available resources from within a single program:
 - One program that runs well (i.e. reasonably close to "hand-tuned" performance) on a heterogeneous mixture of processors.

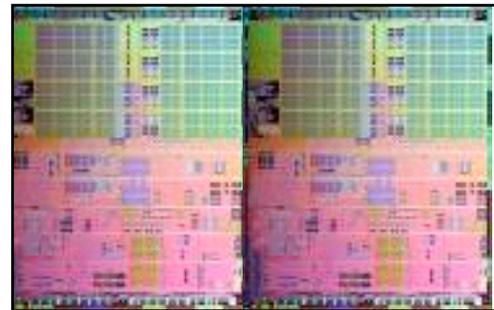


Heterogeneous many core processors

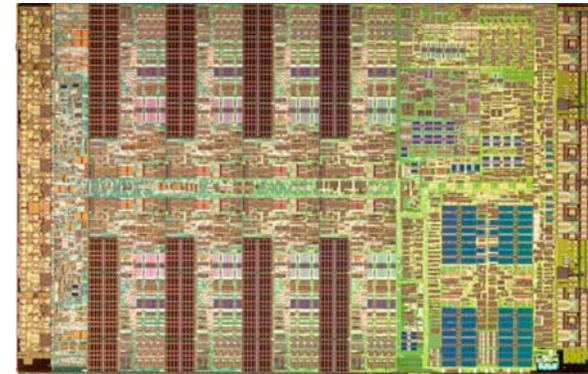
The mass market hardware landscape has never been so chaotic ... and its only going to get worse.



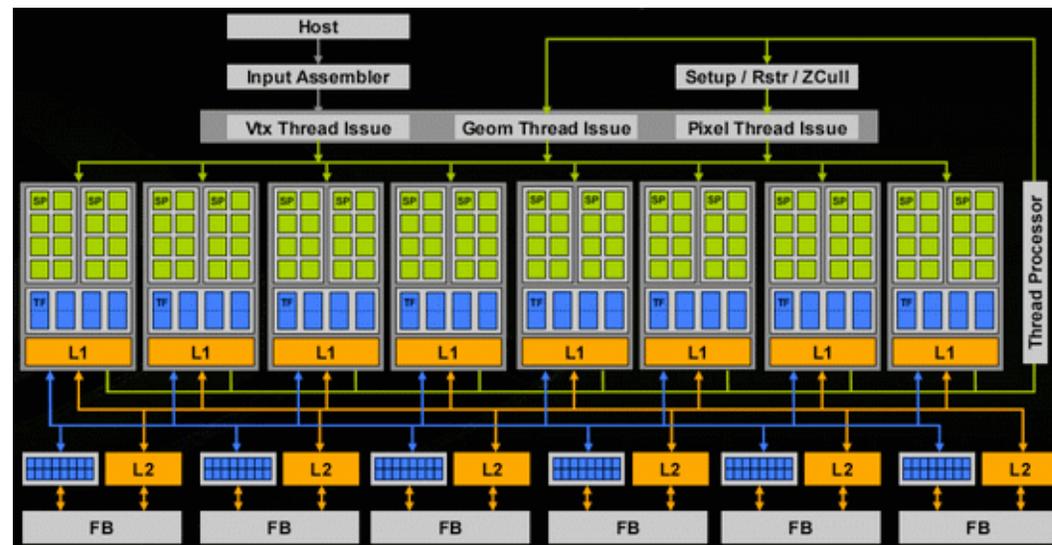
Intel 80 core research chip



Intel Dual Core CPU

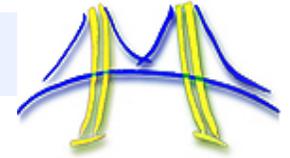
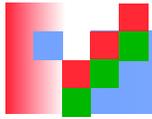


IBM Cell



NVIDIA 8800

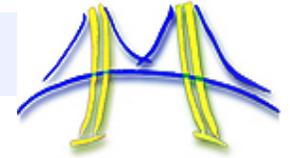
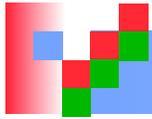
3rd party names are the property of their owners.



The many-core challenge

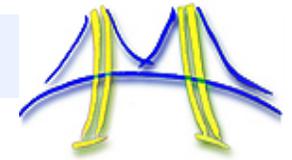
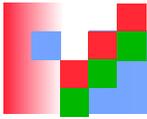
- We have arrived at many-core solutions not because of the success of our parallel software but because of our failure to keep increasing CPU frequency.
- Result: a fundamental and dangerous mismatch
 - Parallel hardware is ubiquitous.
 - Parallel software is rare

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



Patterns and Frameworks

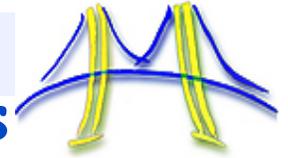
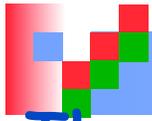
- In the long run, we will provide high level frameworks/scripting-languages that will meet the needs of the domain-expert, application programmers (we hope).
 - Design patterns will guide us to the right framework designs.
- But even in a frameworks world, you need to support the framework programmers
 - (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	CORRELATE	GLU	Mentat	Parafraise2	pC++
ACE	CPS	GUARD	Legion	Paralation	SCHEDULE
ACT++	CRL	HASL.	Meta Chaos	Parallel-C++	SciTL
Active messages	CSP	Haskell	Midway	Parallaxis	SDDA.
Adl	Cthreads	HPC++	Millipede	ParC	SHMEM
Adsmith	CUMULVS	JAVAR.	CparPar	ParLib++	SIMPLE
ADDAP	DAGGER	HORUS	Mirage	ParLin	Sina
AFAPI	DAPPLE	HPC	MpC	Parmacs	SISAL.
ALWAN	Data Parallel C	IMPACT	MOSIX	Parti	distributed smalltalk
AM	DC++	ISIS.	Modula-P	pC	SMI.
AMDC	DCE++	JAVAR	Modula-2*	PCN	SONiC
AppLeS	DDD	JADE	Multipol	PCP:	Split-C.
Amoeba	DICE.	Java RMI	MPI	PH	SR
ARTS	DIPC	javaPG	MPC++	PEACE	Sthreads
Athapascan-0b	DOLIB	JavaSpace	Munin	PCU	Strand.
Aurora	DOME	JIDL	Nano-Threads	PET	SUIF.
Automap	DOSMOS.	Joyce	NESL	PENNY	Synergy
bb_threads	DRL	Khoros	NetClasses++	Phosphorus	Telegrphos
Blaze	DSM-Threads	Karma	Nexus	POET.	SuperPascal
BSP	Ease .	KOAN/Fortran-S	Nimrod	Polaris	TCGMSG.
BlockComm	ECO	LAM	NOW	POOMA	Threads.h++.
C*.	Eiffel	Lilac	Objective Linda	POOL-T	TreadMarks
"C* in C	Eilean	Linda	Occam	PRESTO	TRAPPER
C**	Emerald	JADA	Omega	P-RIO	uC++
CarlOS	EPL	WWWinda	OpenMP	Prospero	UNITY
Cashmere	Excalibur	ISETL-Linda	Orca	Proteus	UC
C4	Express	ParLin	OOF90	QPC++	V
CC++	Falcon	Eilean	P++	PVM	ViC*
Chu	Filaments	P4-Linda	P3L	PSI	Visifold V-NUS
Charlotte	FM	POSYBL	Pablo	PSDM	VPE
Charm	FLASH	Objective-Linda	PADE	Quake	Win32 threads
Charm++	The FORCE	LiPS	PADRE	Quark	WinPar
Cid	Fork	Locust	Panda	Quick Threads	XENOOPS
Cilk	Fortran-M	Lparx	Papers	Sage++	XPC
CM-Fortran	FX	Lucid	AFAPI.	SCANDAL	Zounds
Converse	GA	Maisie	Para++	SAM	ZPL
Code	GAMMA	Manifold	Paradigm		
COOL	Glenda				

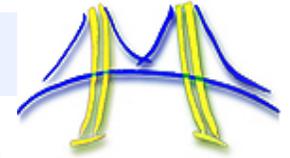
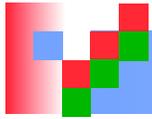
Models from the golden age of parallel programming



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

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AMDC	DCE++	JAVAR	Modula-2*	PCN	SONiC
AppLeS	DDD	JADE	Multipol	PCP:	Split-C.
Amoeba	DICE.	Java RMI	MPI	PH	SR
ARTS	DIPC	javaPG	MPC++	PEACE	Sthreads
Athapascan-0b	DOLIB	JavaSpace	Munin	PCU	Strand.
Aurora	DOME	JIDL	Nano-Threads	PET	SUIF.
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BlockComm	ECO	LAM	NOW	POOMA	Threads.h++.
C*.	Eiffel	Lilac	Objective Linda	POOL-T	TreadMarks
"C* in C	Eilean	Linda	Occam	PRESTO	TRAPPER
C**	Emerald	JADA	Omega	P-RIO	uC++
CarlOS	EPL	WWWinda	OpenMP	Prospero	UNITY
Cashmere	Excalibur	ISETL-Linda	Orca	Proteus	UC
C4	Express	ParLin	OOF90	QPC++	V
CC++	Falcon	Eilean	P++	PVM	ViC*
Chu	Filaments	P4-Linda	P3L	PSI	Visifold V-NUS
Charlotte	FM	POSYBL	Pablo	PSDM	VPE
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Code	GAMMA	Manifold	Paradigm		
COOL	Glenda				

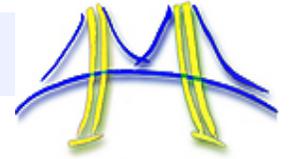
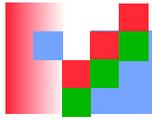
 Programming models I've worked with.



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?

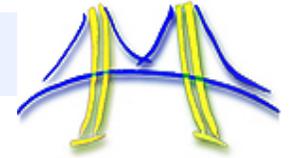
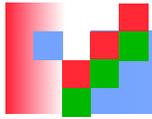


Lesson 1: computer scientists are easily seduced by beauty

- 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



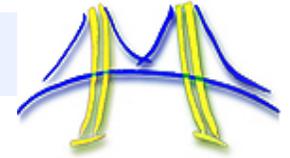
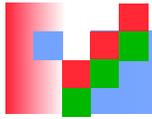
Lesson 2: Software vendors (not academics and not hardware vendors) choose the winning programming models

- 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

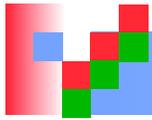
HW details exposed so SW can adapt



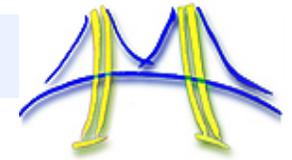
Ugly programming models win!

- 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 th 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, gentype 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, intrn *exp)
 gentype hypot (gentype x, gentype y)
 intrn ilogb (gentype x)
 gentype ldexp (gentype x, intrn n)
 gentype ldexp (gentype x, int n)
 gentype lgamma (gentype x)
 gentype lgamma_r (gentype x, intrn *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)

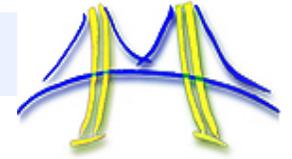
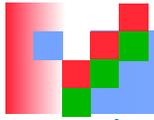
gentype pow (gentype x, gentype y)
 gentype pown (gentype x, intrn y)
 gentype powr (gentype x, gentype y)
 gentype remainder (gentype x, gentype y)
 gentype remquo (gentype x, gentype y, intrn *quo)
 gentype rint (gentype)
 gentype rootn (gentype x, intrn y)
 gentype round (gentype x)
 gentype rsqrt (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 (intrn hi, uintn lo)
 ushortn upsample (uintn hi, uintn lo)
 intrn upsample (intrn hi, uintn lo)
 uintn upsample (uintn hi, uintn lo)
 longn upsample (intrn 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

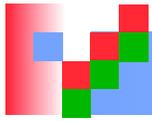
int isequal (float x, float y)
 intrn isequal (floatn x, floatn y)
 int isnotequal (float x, float y)
 intrn isnotequal (floatn x, floatn y)
 int isgreater (float x, float y)
 intrn isgreater (floatn x, floatn y)
 int isgreaterequal (float x, float y)
 intrn isgreaterequal (floatn x, floatn y)
 int isless (float x, float y)
 intrn isless (floatn x, floatn y)
 int islessequal (float x, float y)
 intrn islessequal (floatn x, floatn y)
 int islessgreater (float x, float y)
 intrn islessgreater (floatn x, floatn y)
 int isfinite (float)
 intrn isfinite (floatn)
 int isnan (float)
 intrn isnan (floatn)
 int isnormal (float)
 intrn isnormal (floatn)
 int isordered (float x, float y)
 intrn isordered (floatn x, floatn y)
 int isunordered (float x, float y)
 intrn isunordered (floatn x, floatn y)
 int signbit (float)
 intrn 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,igentype 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, __private 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)

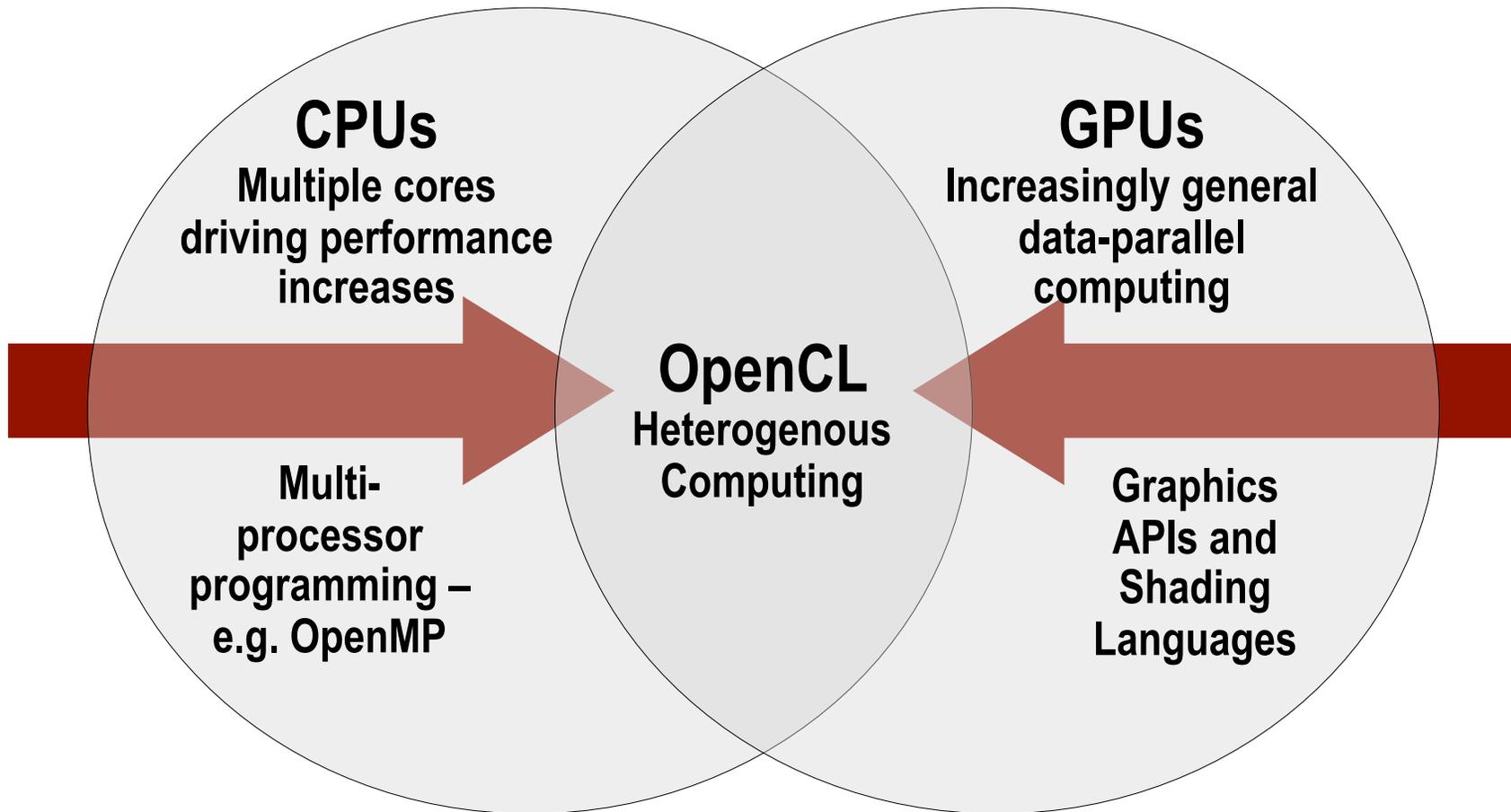
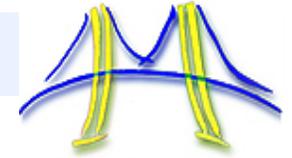


Agenda

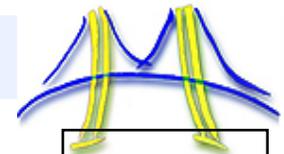
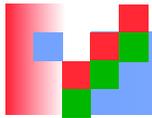
- Ugly programming models and why they rule
- • The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- An OpenCL "deep dive"



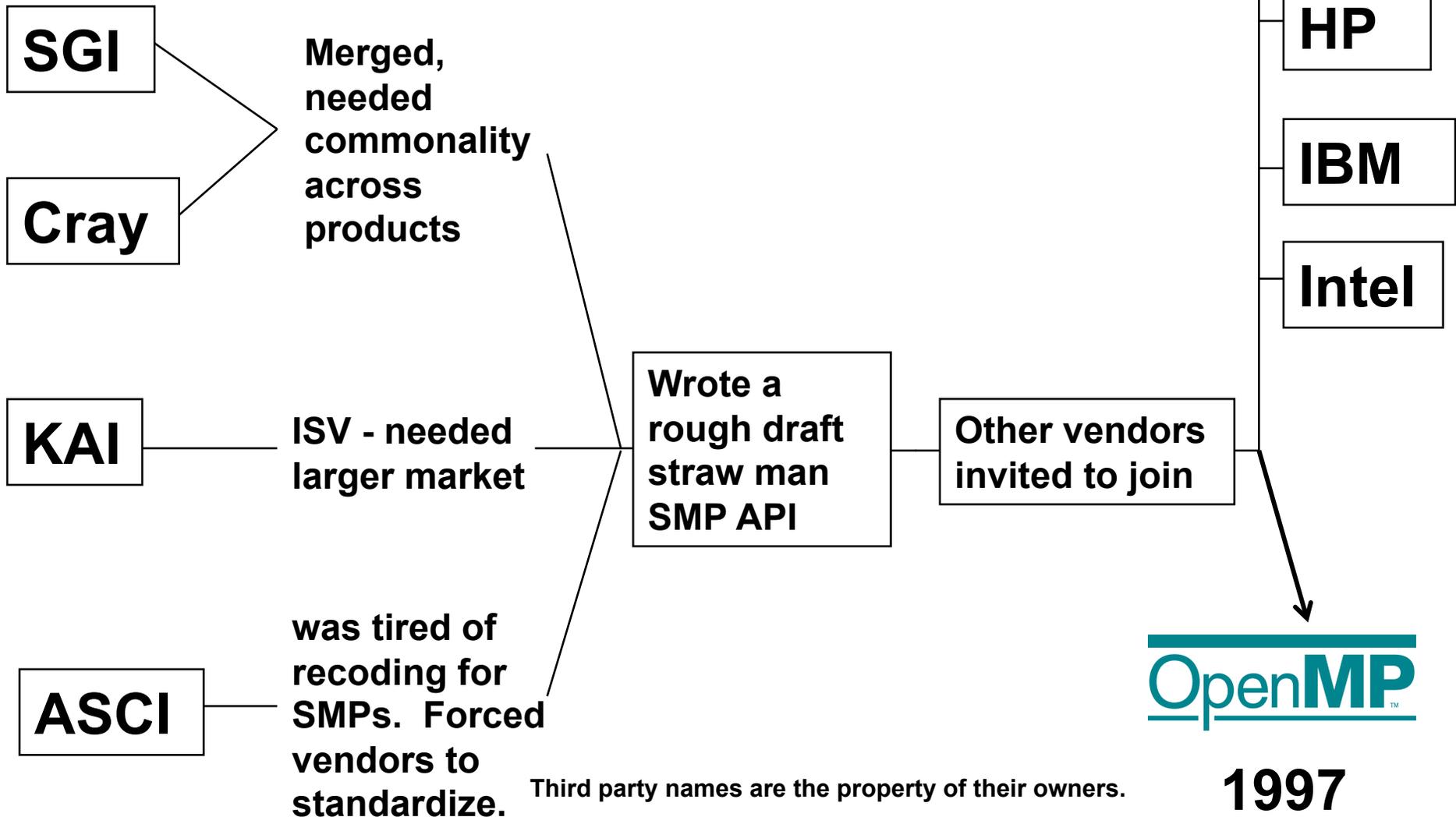
OpenCL ... the ugliest programming model in existence



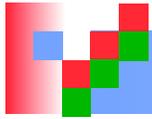
OpenCL – Open Computing Language
Open standard for portable programming of heterogeneous platforms (CPUs, GPUs, and other processors)



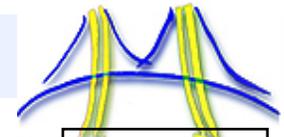
Consider the historical precedent with OpenMP ...



Third party names are the property of their owners.



OpenCL: Can history repeat itself?



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

AMD

Merged,
needed
commonality
across
products

ATI

Nvidia

GPU vendor -
wants to steel mkt
share from CPU

Intel

CPU vendor -
wants to steel mkt
share from GPU

Apple

was tired of recoding
for many core, GPUs.
Pushed vendors to
standardize.

Wrote a
rough draft
straw man
API

Khronos
Compute
group formed

Ericsson

Noikia

IBM

Sony

Blizzard

Freescale

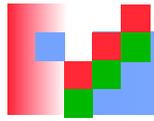
TI

+ many
more

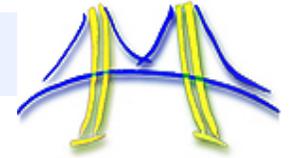
OpenCL

Dec 2008

Third party names are the property of their owners.



OpenCL Working Group



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

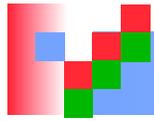


KHRONOS
GROUP

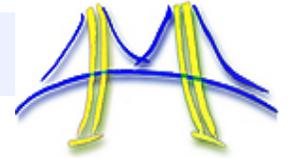
8/20/09

Tim Mattson

OpenCL: 17

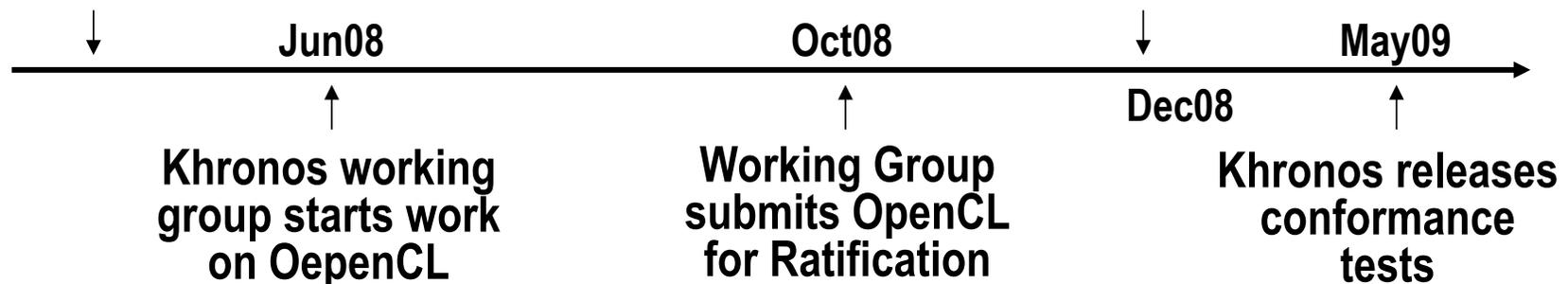


OpenCL Timeline

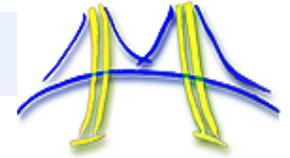
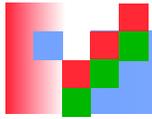


Apple, AMD, Intel,
NVIDIA write draft
proposal

Khronos
releases OpenCL
specification



- 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 released a CPU OpenCL SIGGRAPH'09
 - Intel actively promotes OpenCL, but we have not announced our product strategy for OpenCL yet.



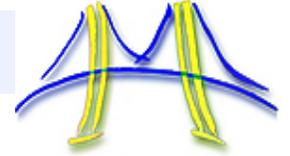
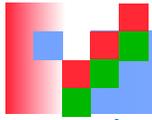
OpenCL 1.0 Embedded Profile

- 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



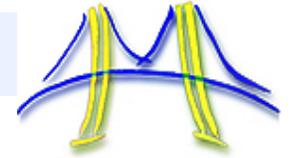
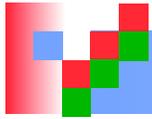
A camera phone with GPS processes images to recognize buildings and landmarks and provides relevant data from internet

Source: Kari Pulli, Noikia



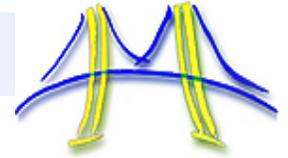
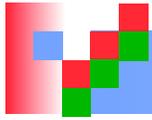
Agenda

- 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"



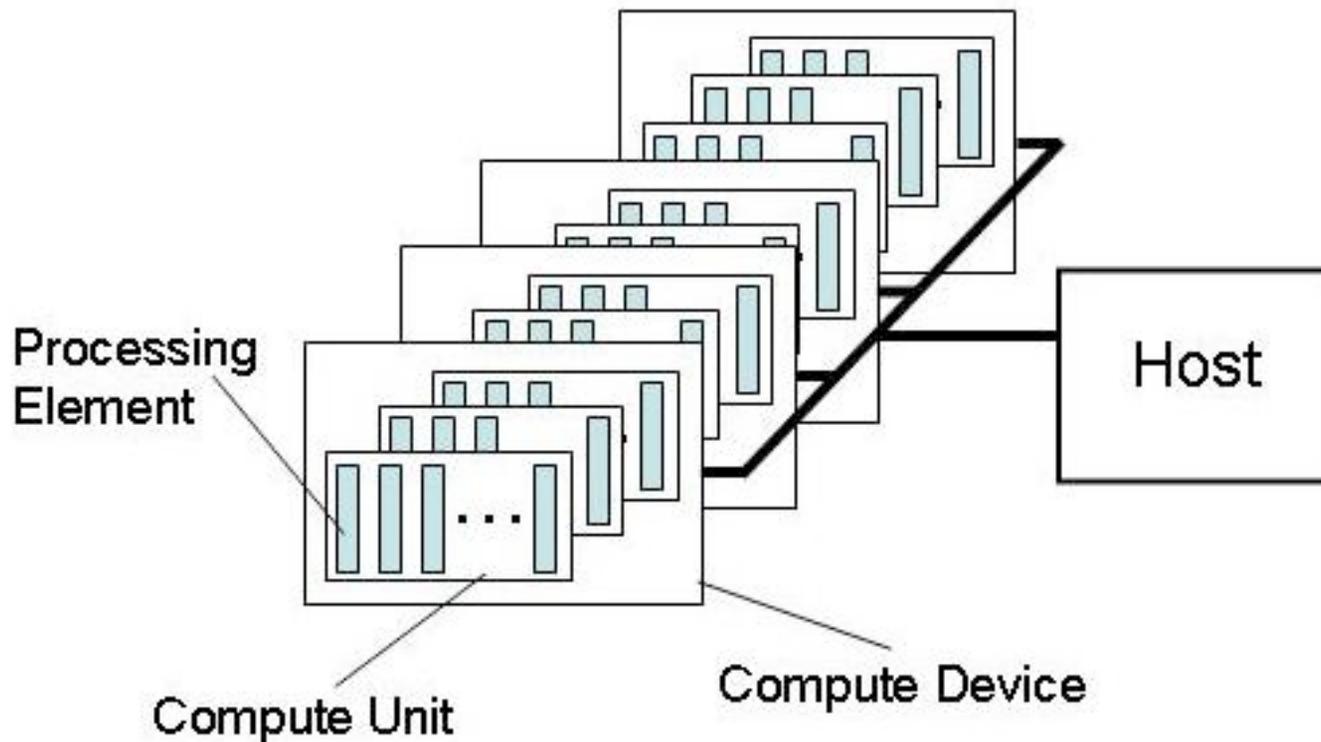
OpenCL: high level view

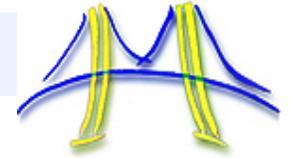
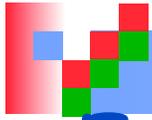
- OpenCL applications:
 - A host program running on the PC
 - One or more *Kernels* that are queued up to run on CPUs, GPUs, and "other processors".
- OpenCL is understood in terms of these models
 - Platform model
 - Execution model
 - Memory model
 - Programming model



OpenCL Platform model

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

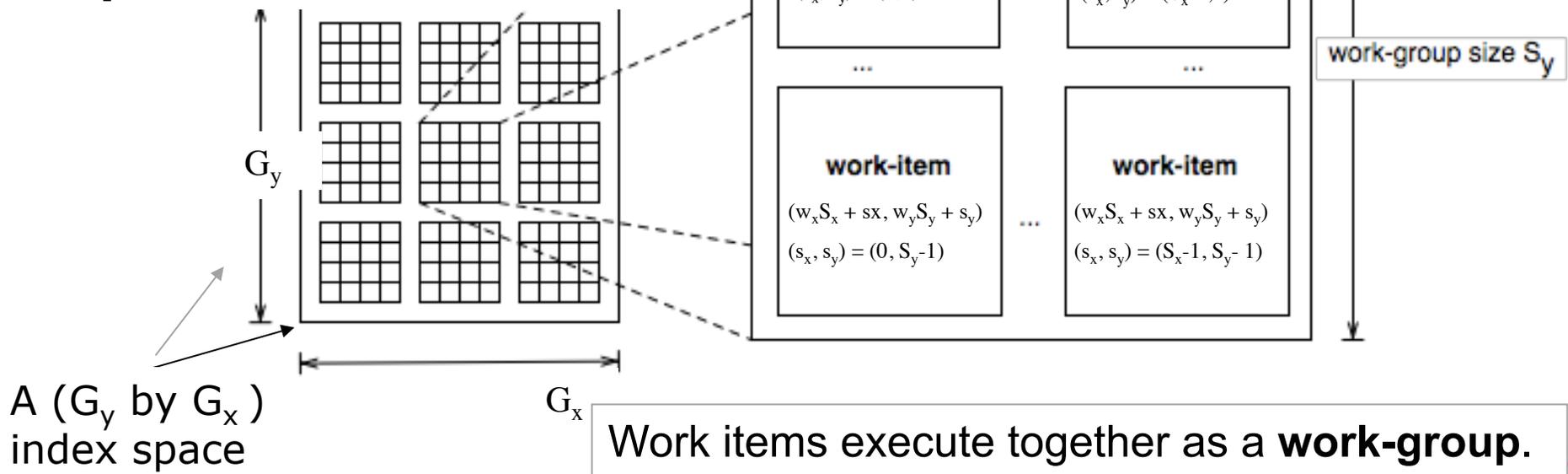


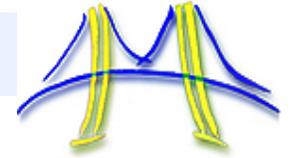
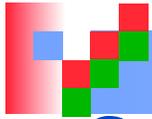


Execution Model

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

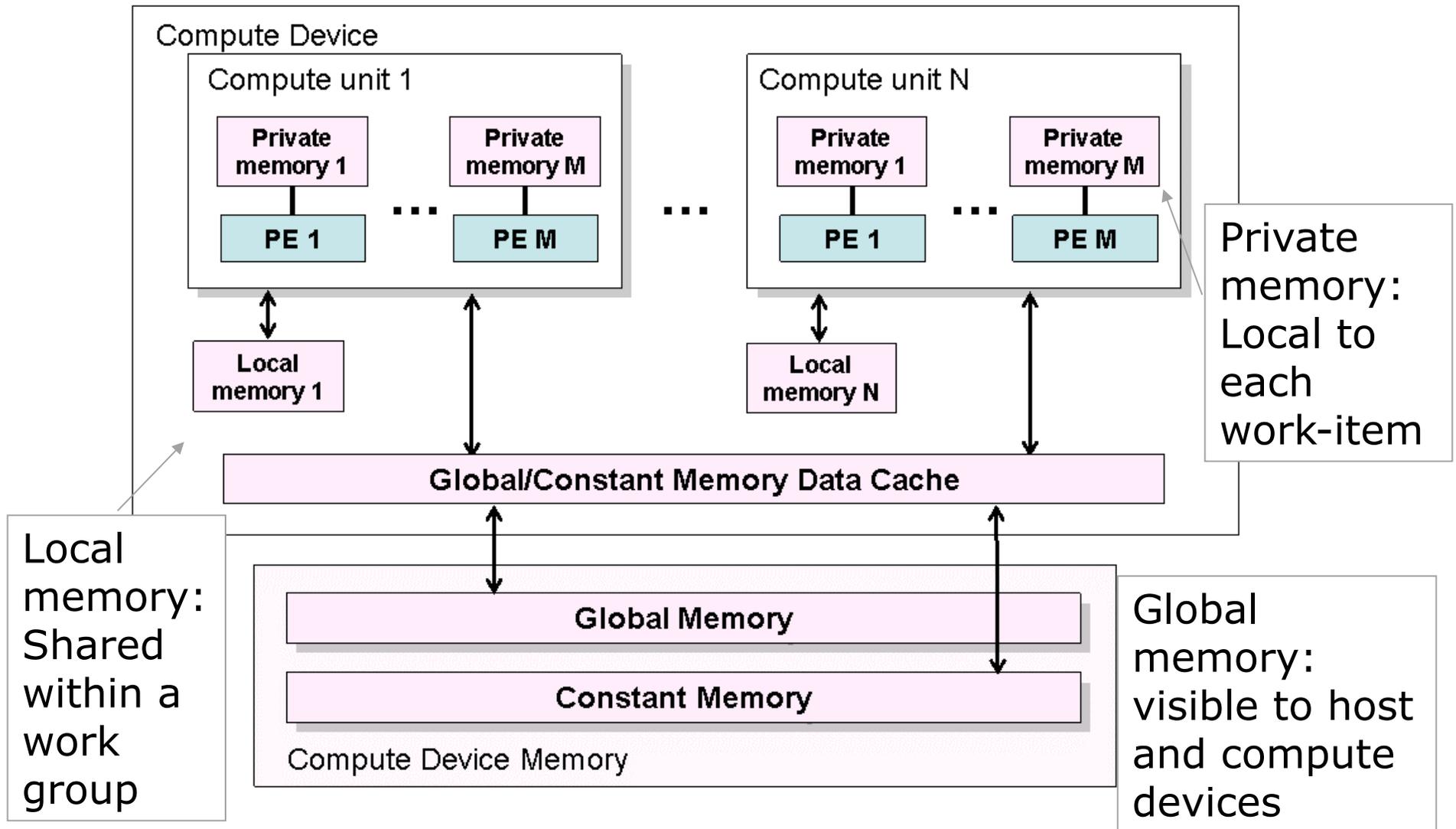
Kernel execution commands launch **work-items**: i.e. a kernel for each point in an abstract **Index Space**

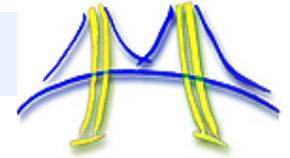
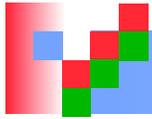




OpenCL Memory model

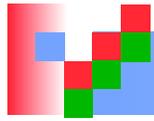
- Implements a relaxed consistency, shared memory model



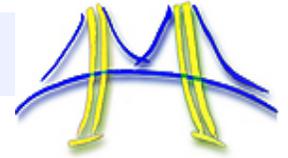


OpenCL programming model

- 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.

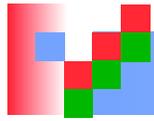


Programming Kernels: OpenCL C Language

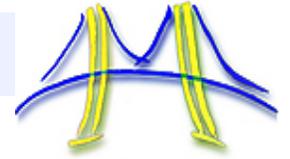


- Derived from ISO C99
 - No standard C99 headers, function pointers, recursion, variable length arrays, and bit fields
- Additions to the language for parallelism
 - Work-items and workgroups
 - Vector types
 - Synchronization
- Address space qualifiers
- Optimized image access
- Built-in functions

Acknowledgement: Aaftab Munshi of Apple

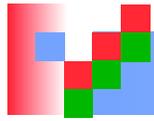


OpenCL C: Data Types

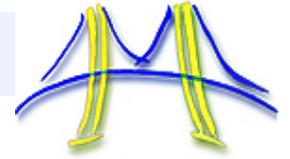


- Scalar data types
 - char , uchar, short, ushort, int, uint, long, ulong
 - bool, intptr_t, ptrdiff_t, size_t, uintptr_t, void, half (storage)
- Image types
 - image2d_t, image3d_t, sampler_t
- Vector data types

Acknowledgement: Aaftab Munshi of Apple

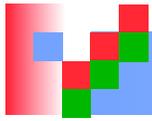


OpenCL C: Vector Types

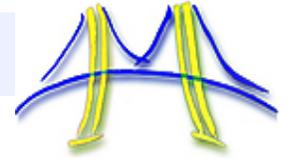


- Portable
- Vector length of 2, 4, 8, and 16
- char2, ushort4, int8, float16, ...
- Endian safe
- Aligned at vector length
- Vector operations and built-in functions

Acknowledgement: Aaftab Munshi of Apple



Vector Operations

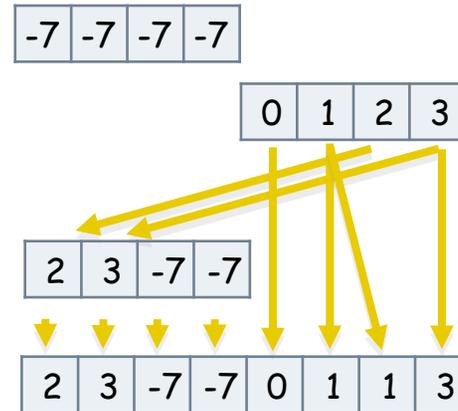


- Vector literal

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

- Vector components

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



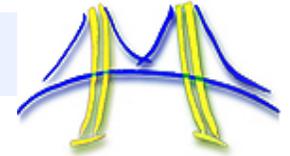
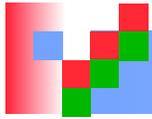
- Vector ops

```
vi0 += vi1;
```

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

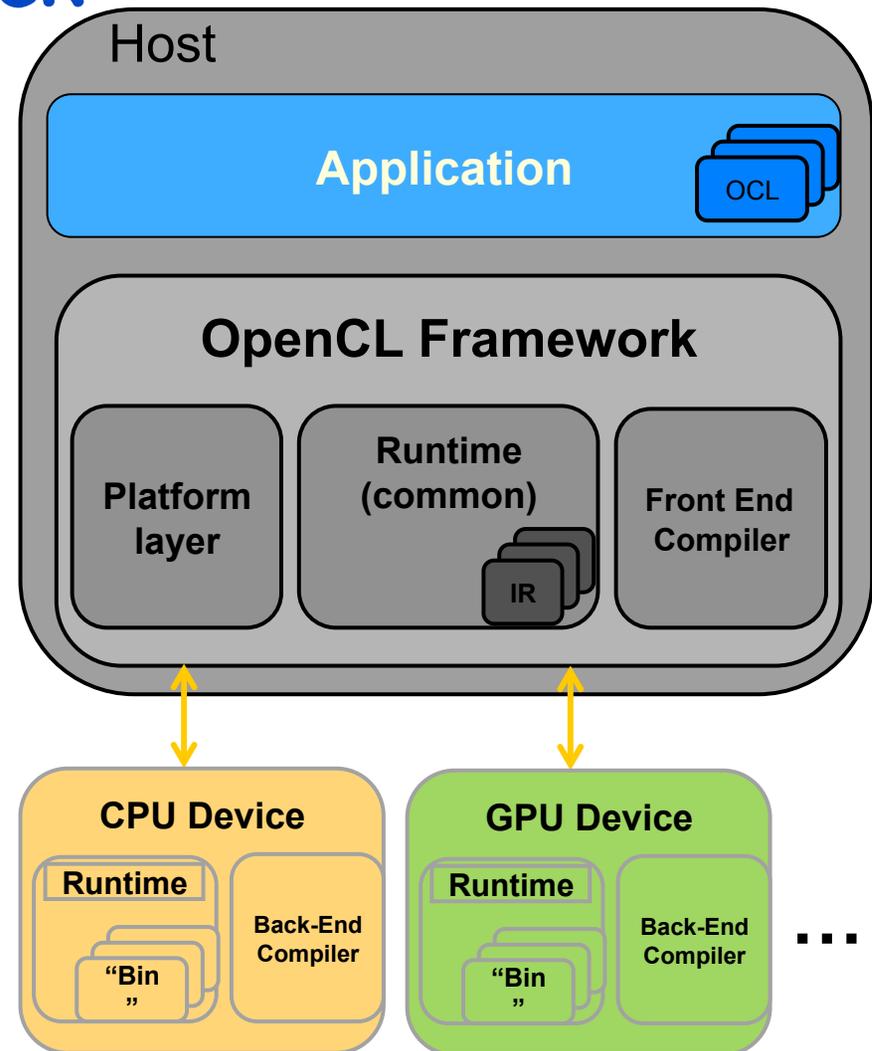


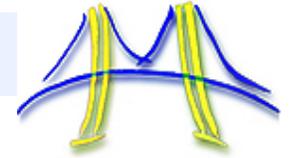
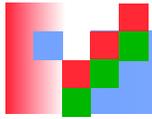
Acknowledgement: Aaftab Munshi of Apple



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



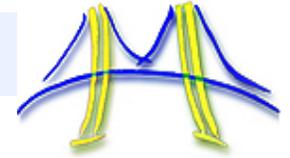
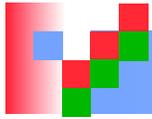


Example: vector addition

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

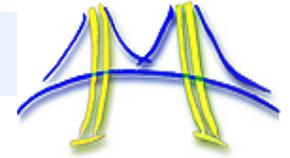
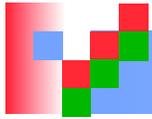
$$C[i] = A[i] + B[i] \quad \text{for } i=1 \text{ to } N$$

- 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);

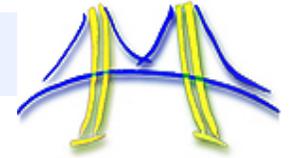
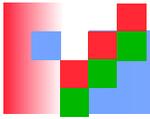
// set the args values
err = clSetKernelArg(kernel, 0, (void *) &memobjs[0],
    sizeof(cl_mem));
err |= clSetKernelArg(kernel, 1, (void *) &memobjs[1],
    sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *) &memobjs[2],
    sizeof(cl_mem));

// 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

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

Define platform and queues

```
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
program = clCreateProgramWithSource(context, 1,
                                   &program_source, NULL, NULL);
```

Create the program

Build the program

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

Create and setup kernel

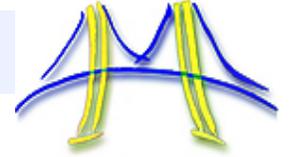
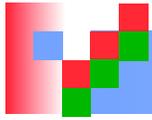
```
kernel = clCreateKernel(program, "k", &err);
err = clSetKernelArg(kernel, 0, (void *) &memobjs[0],
                    sizeof(cl_mem));
err |= clSetKernelArg(kernel, 1, (void *) &memobjs[1],
                    sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *) &memobjs[2],
                    sizeof(cl_mem));
```

Execute the kernel

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

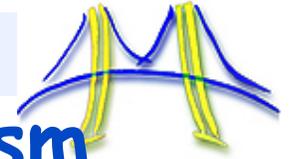
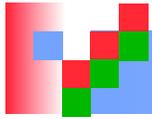
Read results on the host

```
err = clReadBuffer(cmd_queue, memobjs[2], CL_TRUE,
                  0, n * sizeof(cl_float), dst, 0, NULL, NULL);
```



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"

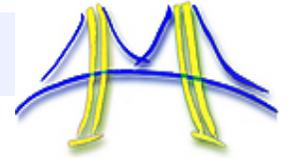


OpenCL's Two Styles of Data-Parallelism

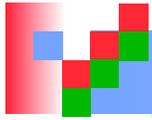
- Explicit SIMD data parallelism:
 - The kernel defines one stream of instructions
 - Parallelism from using wide vector types
 - Size vector types to match native HW width
 - Combine with task parallelism to exploit multiple cores.
- Implicit SIMD data parallelism (i.e. shader-style):
 - Write the kernel 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

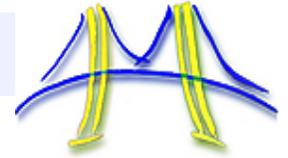
Data-Parallelism: options on IA processors



- Explicit SIMD data parallelism
 - Programmer chooses vector data type (width)
 - Compiler hints using attributes
 - » `vec_type_hint(typen)`
- 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



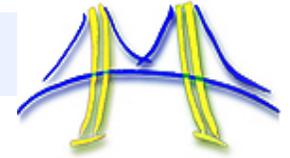
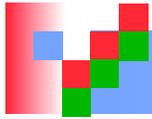
- OpenCL as a portable interface to vector instruction sets.
 - Block loops and pack data into vector types (float4, ushort16, etc).
 - Replace scalar ops in loops with blocked loops and vector ops.
 - Unroll loops, optimize indexing to match machine vector width

```
float a[N], b[N], c[N];
for (i=0; i<N; i++)
    c[i] = a[i]*b[i];

<<< the above becomes >>>>

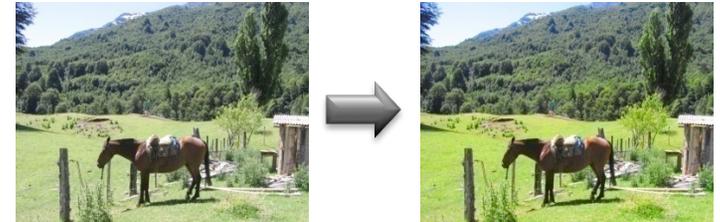
float4 a[N/4], b[N/4], c[N/4];
for (i=0; i<N/4; i++)
    c[i] = a[i]*b[i];
```

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



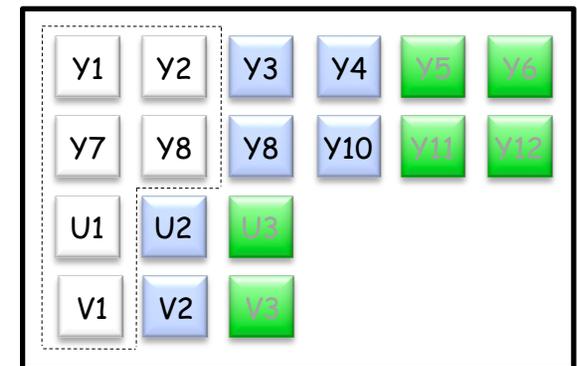
Video Processing Case Study

- 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

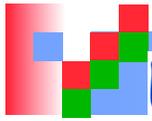


Video Frames

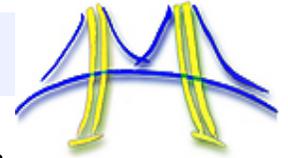
- Processed in YUV 4:2:0 planar color space
- 10 bits per color component
 - » Contained in *ushort* (unsigned short)
- Fixed point arithmetic
- Structure of arrays (SOA)



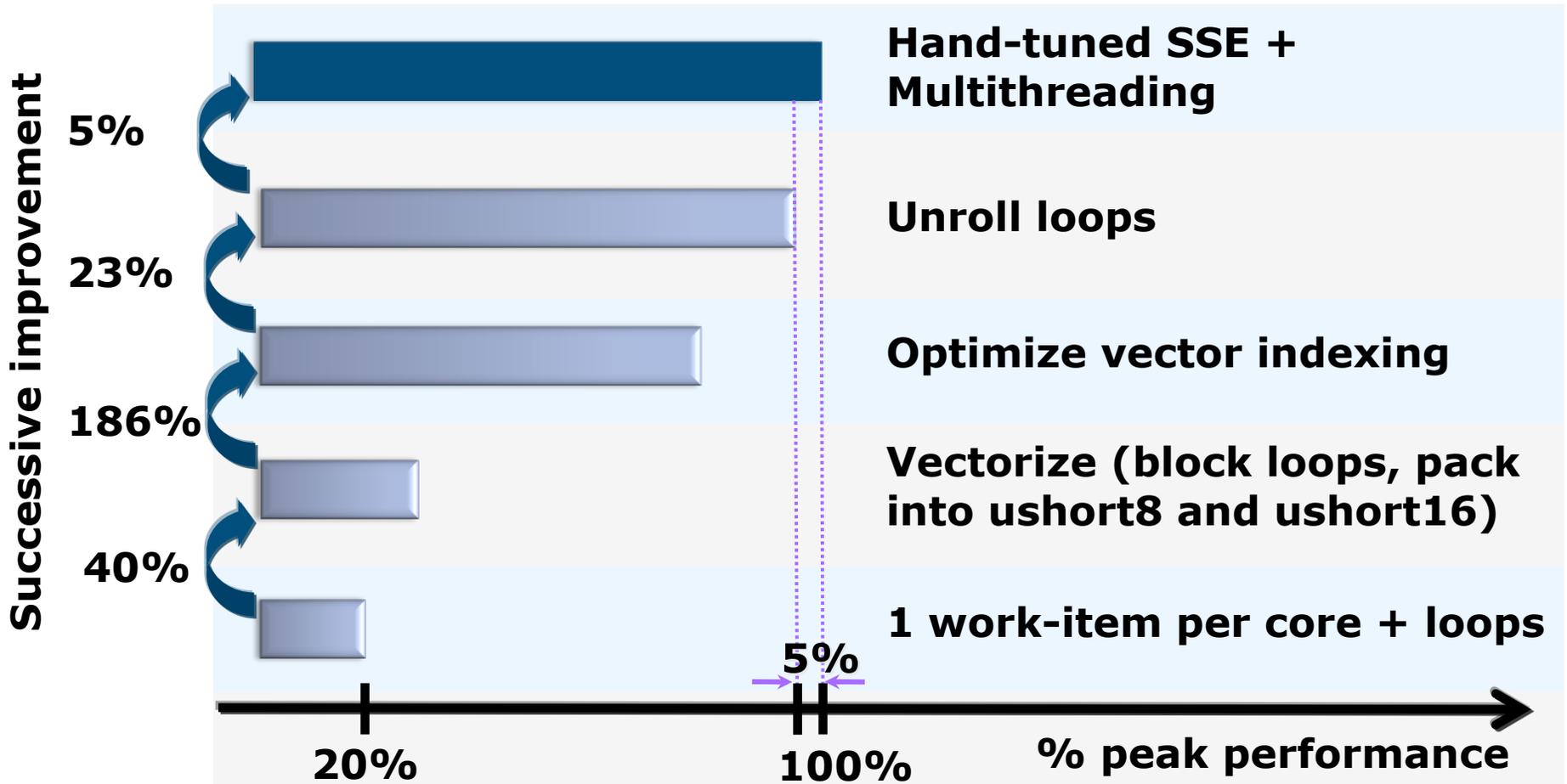
YUV 4:2:0 Frame



Explicit SIMD data parallelism: Case Study



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

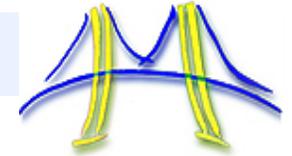
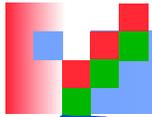


Good news: OpenCL code 95% of hand-tuned SSE/MT perf.

Bad news: New platform, redo all those optimizations.

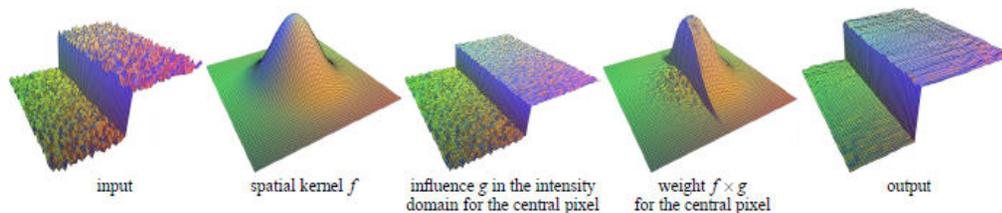
3 Ghz dual core CPU
pre-release version of OpenCL
Source: Intel Corp.

* 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.

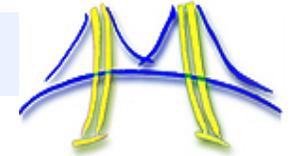
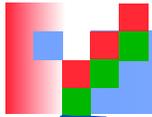


Towards "Portable" Performance

- 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];
        }
    }
}
```

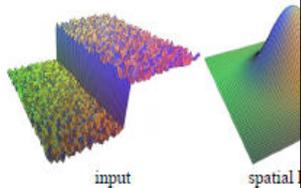


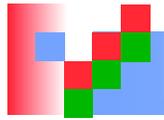
Towards "Portable" Performance

- The following example
- Reminder: edge processing
- See more at <http://sci.psych221/bilati.htm>

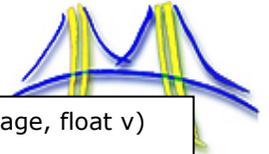
```
void P4_Bilateral9 (int start, int end, float v)
{
    <<< Declarations >>>
    for (i = start; i < end; i++) {
        for (j = 1; j <= 4; j++) {
            <<< a series of short loops >>>
        }
        for (j = 1; j <= 4; j++) {
            <<< a 2nd series of short loops >>>
        }
  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

```
void P4_Bilateral9 (int start, int end, float v)
{
```





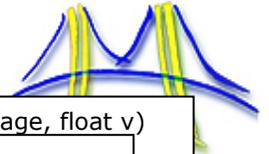
"Implicit SIMD" data parallel code



- "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;
}
```

“Implicit SIMD” data parallel code



```
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 >>>

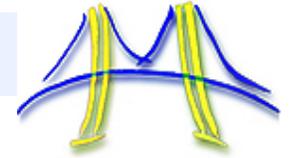
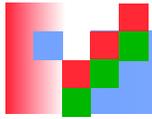
    for (size_t dist = 1; dist <= maxDistance; ++dist){
      neighborPixel = inImage[myID +
                          dist*IMAGE_WIDTH];
      diff = neighborPixel - currentPixel;
      currentWeights = exp(diff * diff * inv_of_2v);
      << plus others to compute pixels, weights, etc >>
      accumulatedWeights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

Source: Intel Corp.

8/20/09

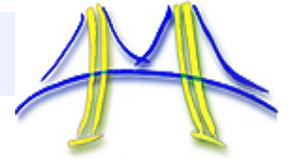
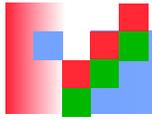
Tim Mattson

OpenCL: 44



Portable Performance in OpenCL

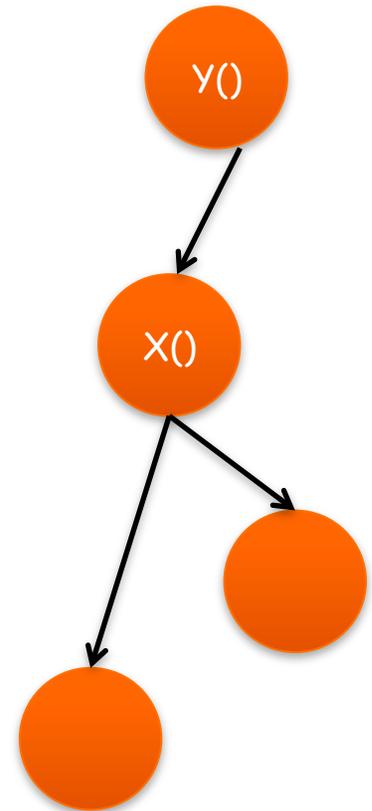
- Implicit SIMD code ... where the framework maps work-items onto the “lanes of the vector unit” ... creates the opportunity for portable code that performs well on full range of OpenCL compute devices.
- Requires mature OpenCL technology that “knows” how to do this:
 - ... But it is important to note ... we know this approach works since its based on the way shader compilers work today.

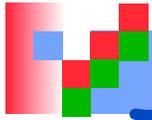


Task Parallelism Overview

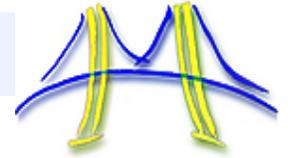
- Think of a task as an asynchronous function call
 - "Do X at some point in the future"
 - Optionally "... after Y is done"
 - Light weight, often in user space
- Strengths
 - Copes well with heterogeneous workloads
 - Doesn't require 1000's of strands
 - Scales well with core count
- Limitations
 -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

A natural fit to multi-core CPUs

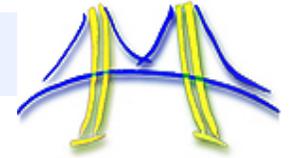
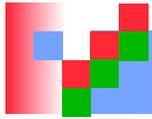




Task Parallelism in OpenCL

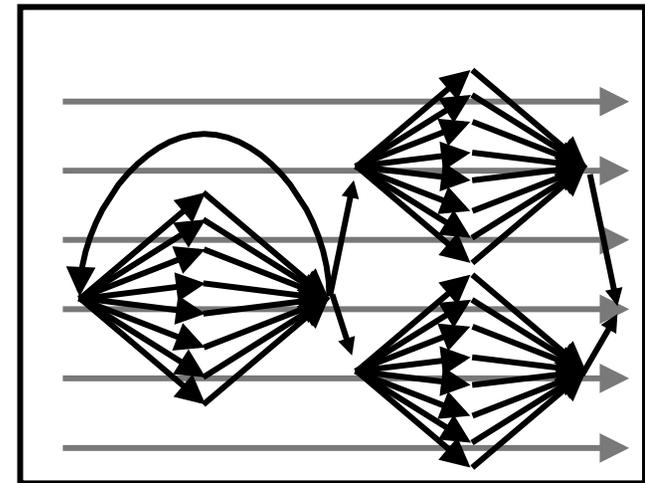


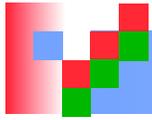
- `clEnqueueTask`
 - Imagine "sea of different tasks" executing concurrently
 - A task "owns the core" (i.e., a workgroup size of 1)
- Use tasks when algorithm...
 - Benefits from large amount of local/private memory
 - Has predictable global memory accesses
 - Can be programmed using explicit vector 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



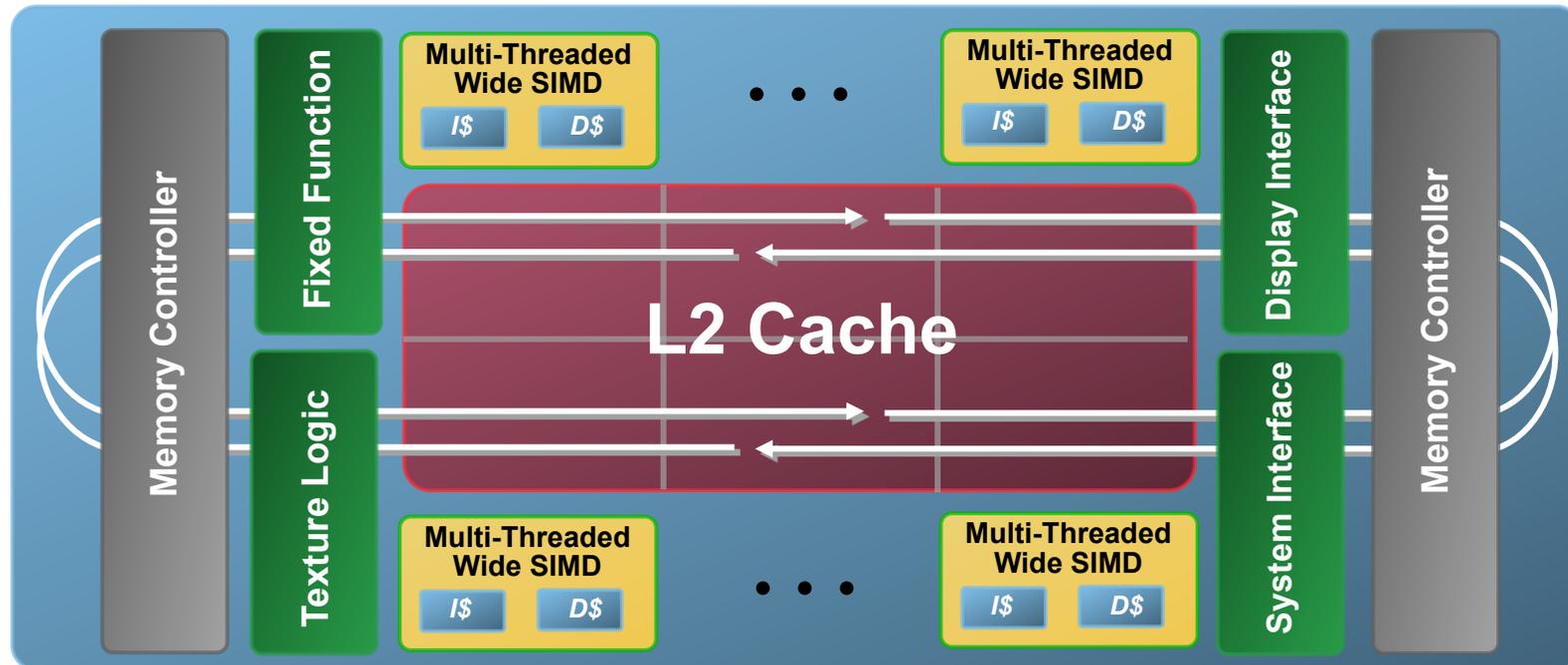
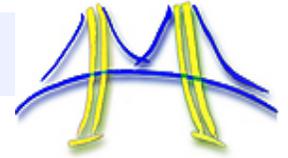
Future Parallel Programming

- 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



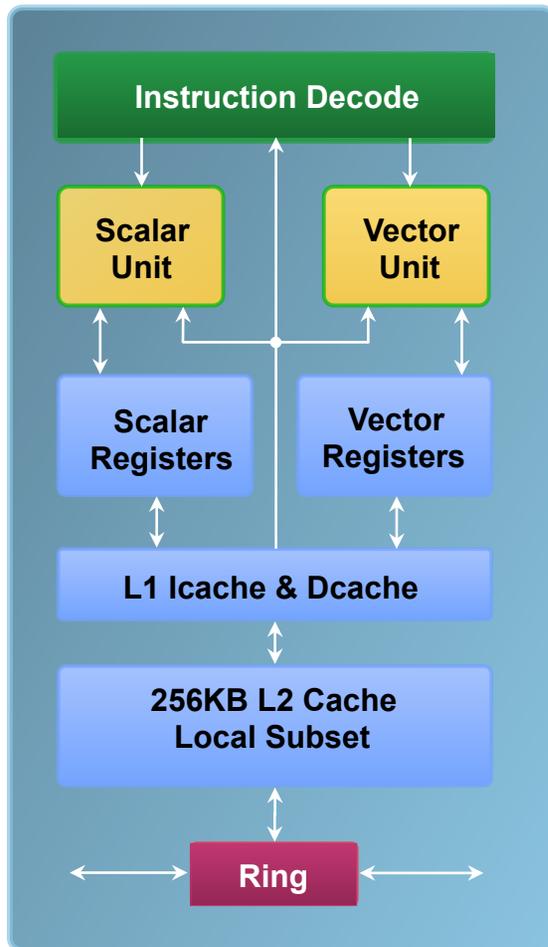
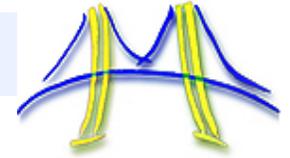


Future parallel programming: Larrabee

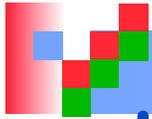


- Cores communicate on a wide ring bus
 - Fast access to memory and fixed function blocks
 - Fast access for cache coherency
- L2 cache is partitioned among the cores
 - Provides high aggregate bandwidth
 - Allows data replication & sharing

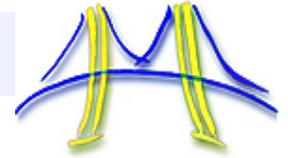
Processor Core Block Diagram



- 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

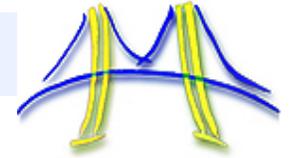
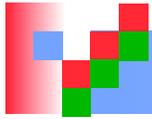


Key Differences from Typical GPUs



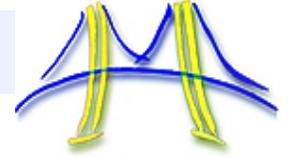
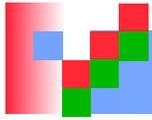
- Each Larrabee core is a complete Intel processor
 - Context switching & pre-emptive multi-tasking
 - Virtual memory and page swapping, even in texture logic
 - Fully coherent caches at all levels of the hierarchy
- Efficient inter-block communication
 - Ring bus for full inter-processor communication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

***Larrabee is perfect for the braided parallelism
in future applications***



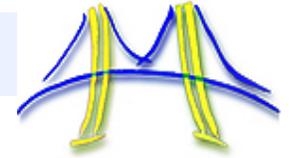
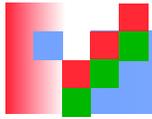
Conclusion

- 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.



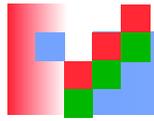
References

- **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

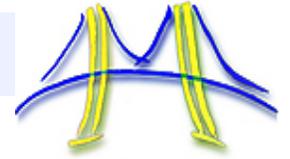


Agenda

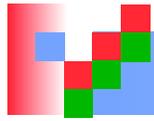
- Ugly programming models and why they rule
- The origin of OpenCL
- A high level view of OpenCL
- OpenCL and the CPU
- • An OpenCL "deep dive"



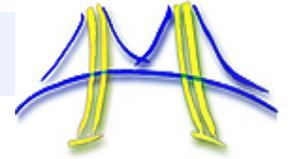
Basic OpenCL Program Structure



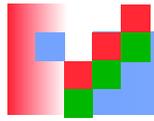
- Host program
 - Query compute devices
 - Create contexts
 - Create memory objects associated to contexts
 - Compile and create kernel program objects
 - Issue commands to command-queue
 - Synchronization of commands
 - Clean up OpenCL resources
- Kernels
 - C code with some restrictions and extensions



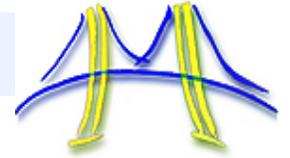
Example: Vector Addition



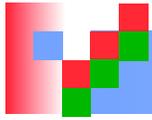
- Compute $c = a + b$
 - a , b , and c are vectors of length N
- Basic OpenCL concepts
 - Simple kernel code
 - Basic context management
 - Memory allocation
 - Kernel invocation



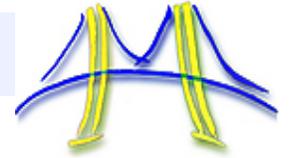
Platform Layer: Basic discovery



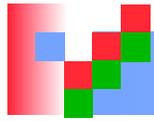
- Platform layer allows applications to query for platform specific features
- Querying platform info Querying devices
 - *clGetDeviceIDs()*
 - » Find out what compute devices are on the system
 - » Device types include CPUs, GPUs, or Accelerators
 - *clGetDeviceInfo()*
 - » Queries the capabilities 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



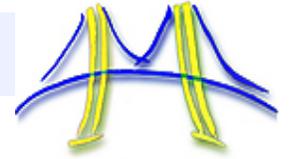
Platform Layer: Contexts



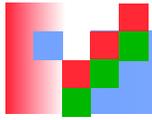
- Creating contexts
 - Contexts are used by the OpenCL runtime to manage objects and execute kernels on one or more devices
 - Contexts are associated to one or more devices
 - » Multiple contexts could be associated to the same device
 - *clCreateContext()* and *clCreateContextFromType()* returns a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



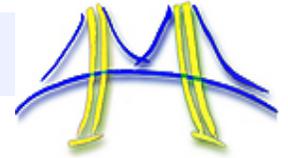
Platform layer: Command-Queues



- 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



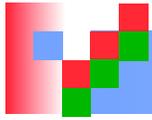
VecAdd: Context, Devices, Queue



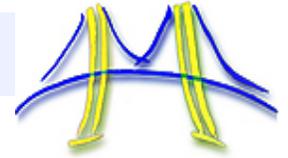
```
// create the OpenCL context on a GPU device
cl_context context = clCreateContextFromType(0, // (must be 0)
      CL_DEVICE_TYPE_GPU,
      NULL, // error callback
      NULL, // user data
      NULL); // error code

// 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);

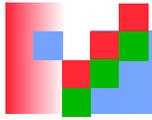
// create a command-queue
cl_cmd_queue cmd_queue = clCreateCommandQueue(context,
      devices[0], 0, // default options
      NULL); // error code
```



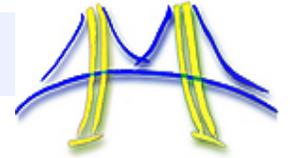
Memory Objects



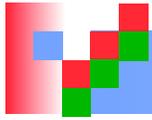
- **Buffer objects**
 - One-dimensional collection of objects (like *C* arrays)
 - Valid elements include scalar and vector types as well as user defined structures
 - Buffer objects can be accessed via pointers in the kernel
- **Image objects**
 - Two- or three-dimensional texture, frame-buffer, or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



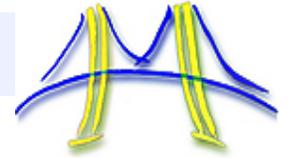
Creating Memory Objects



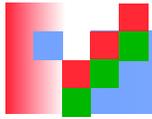
- *clCreateBuffer()*, *clCreateImage2D()*, and *clCreateImage3D()*
- Memory objects are created with an associated context
- Memory can be created as read only, write only, or read-write
- Where objects are created in the platform memory space can be controlled
 - Device memory
 - Device memory with 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



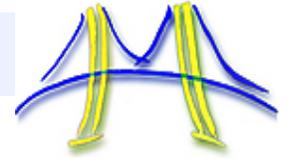
Manipulating Object Data



- 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()*



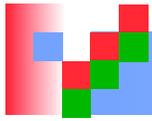
VecAdd: Create Memory Objects



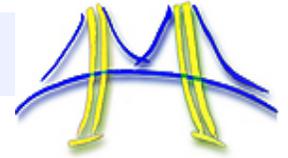
```
cl_mem memobjs[3];
// allocate input buffer memory objects
memobjs[0] = clCreateBuffer(context,
                           CL_MEM_READ_ONLY |    // flags
                           CL_MEM_COPY_HOST_PTR,
                           sizeof(cl_float)*n,  // size
                           srcA,     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

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

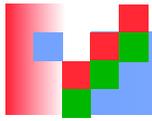
// allocate input buffer memory object
memobjs[2] = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                           sizeof(cl_float)*n, NULL, NULL);
```



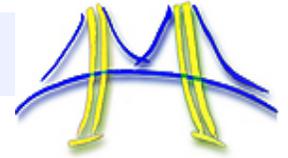
Program Objects



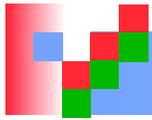
- Program objects encapsulate:
 - An associated context
 - Program source or binary
 - list of targeted devices, build options
 - Number of attached kernel objects
- Build process
 1. Create program object
 - » `clCreateProgramWithSource()`
 - » `clCreateProgramWithBinary()`
 2. Build program executable
 - » 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



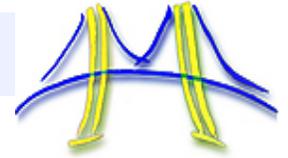
Kernel Objects



- 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



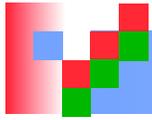
VecAdd: Program and Kernel



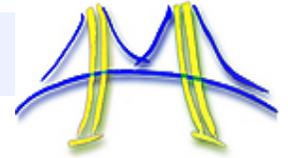
```
// create the program
cl_program program = clCreateProgramWithSource(
    context,
    1,          // string count
    &program_source, // program strings
    NULL,      // string lengths
    NULL);    // error code

// 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);
```



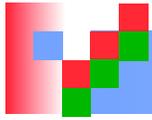
VecAdd: Set Kernel Arguments



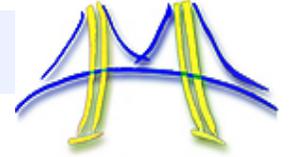
```
// set "a" vector argument
err = clSetKernelArg(kernel,
                    0, // argument index
                    (void *)&memobjs[0], // argument data
                    sizeof(cl_mem)); // argument data size

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

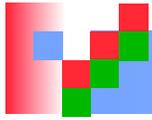
// set "c" vector argument
err |= clSetKernelArg(kernel, 2, (void *)&memobjs[2],
                    sizeof(cl_mem));
```



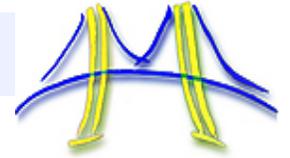
Kernel Execution



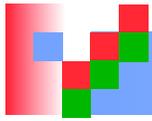
- A command to execute a kernel must be enqueued to the command-queue
- *clEnqueueNDRangeKernel()*
 - Data-parallel execution model
 - Describes the *index space* for kernel execution
 - Requires information on NDRange dimensions and work-group size
- *clEnqueueTask()*
 - Task-parallel execution model (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



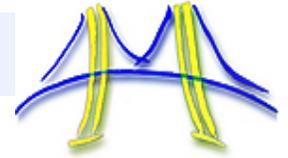
Command-Queues



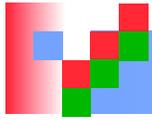
- Command-queue execution
 - Execution model signals when commands are complete or data is ready
 - Command-queue could be explicitly flushed to the device
 - Command-queues execute in-order or out-of-order
 - » In-order - commands complete in the order queued and correct memory is consistent
 - » Out-of-order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



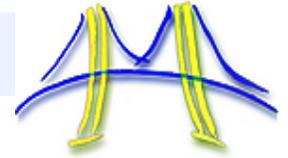
Synchronization



- 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

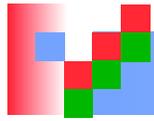


VecAdd: Invoke Kernel, Read Output

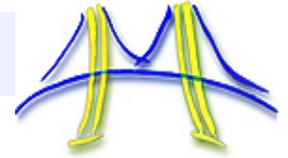


```
size_t global_work_size[1] = n; // set work-item dimensions
// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel,
                             1,          // Work dimensions
                             NULL,      // must be NULL (work offset)
                             global_work_size,
                             NULL,      // automatic local work size
                             0,         // no events to wait on
                             NULL,      // event list
                             NULL);    // event for this kernel

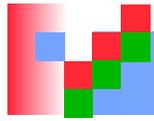
// read output array
err = clEnqueueReadBuffer(context, memobjs[2],
                          CL_TRUE,     // blocking
                          0,           // offset
                          n*sizeof(cl_float), // size
                          dst,         // pointer
                          0,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



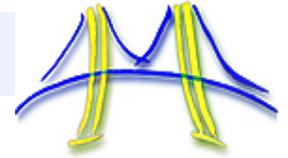
OpenCL C for Compute Kernels



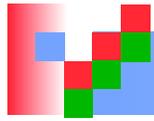
- Derived from ISO C99
 - A few restrictions: recursion, function pointers, functions in C99 standard headers ...
 - Preprocessing directives defined by C99 are supported
- Built-in Data Types
 - Scalar and vector data types, Pointers
 - Data-type conversion functions: `convert_type<_sat><_roundingmode>`
 - 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



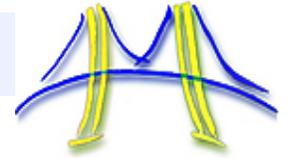
OpenCL C Language Highlights



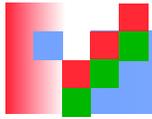
- Function qualifiers
 - “__kernel” qualifier declares a function as a kernel
 - Kernels can call other kernel functions
- Address space qualifiers
 - __global, __local, __constant, __private
 - Pointer kernel arguments must be declared with an address space qualifier
- Work-item functions
 - Query work-item 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



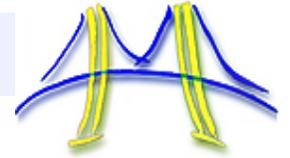
OpenCL C Language Restrictions



- 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

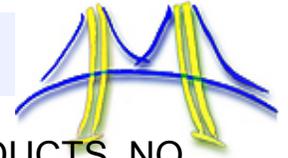


Vector Addition Kernel

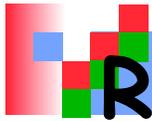


```
__kernel void vec_add (__global const float *a,  
                       __global const float *b,  
                       __global          float *c)  
{  
    int gid = get_global_id(0);  
    c[gid] = a[gid] + b[gid];  
}
```

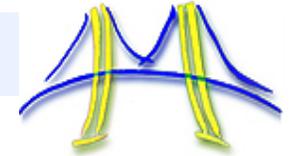
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