The RapidMind Development Platform and Data-Parallel Programming

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Agenda

- Company background
- Product overview
- Basic tutorial
- Loop conversion example
- Application examples

Company

- Technology based on over five years of research at the University of Waterloo
  - One of first research labs to attempt GP-GPU in 1999
  - Developed language prototypes on simulator in 2001
  - Original publications in 2002 on metaprogrammed interface
- Company incorporated in June 2004
- VC Financing totaling $11.3M to date
- Product targets “High-Productivity Computing”
  - Easy to use, high performance, portable SW development
  - Targets GPUs and Cell BE
  - Extension to multi-core CPU now under development

Product

- RapidMind Platform
  - ***Programming middleware for many-core processors***
  - Single-source solution for portable parallel programming
  - Safe and deterministic data-parallel programming model
  - Scalable to arbitrary number of cores
  - Integrates with existing C++ compilers
- Write once, run on multiple targets
  - NVIDIA GPUs
  - ATI GPUs
  - Cell BE
  - Prototype demonstration on quad-core CPU

Product Benefits

- Programmability
  - No new tools or workflows
  - No need for low-level understanding of the target device
  - General purpose
- Portability
  - Application programming independent of OS or target device
- Performance
  - Automatically leverages *all* available computational resources
  - Optimizes code using dynamic runtime compilation
  - C++ overhead “compiled out” of generated code
  - Can significantly *outperform* native tools

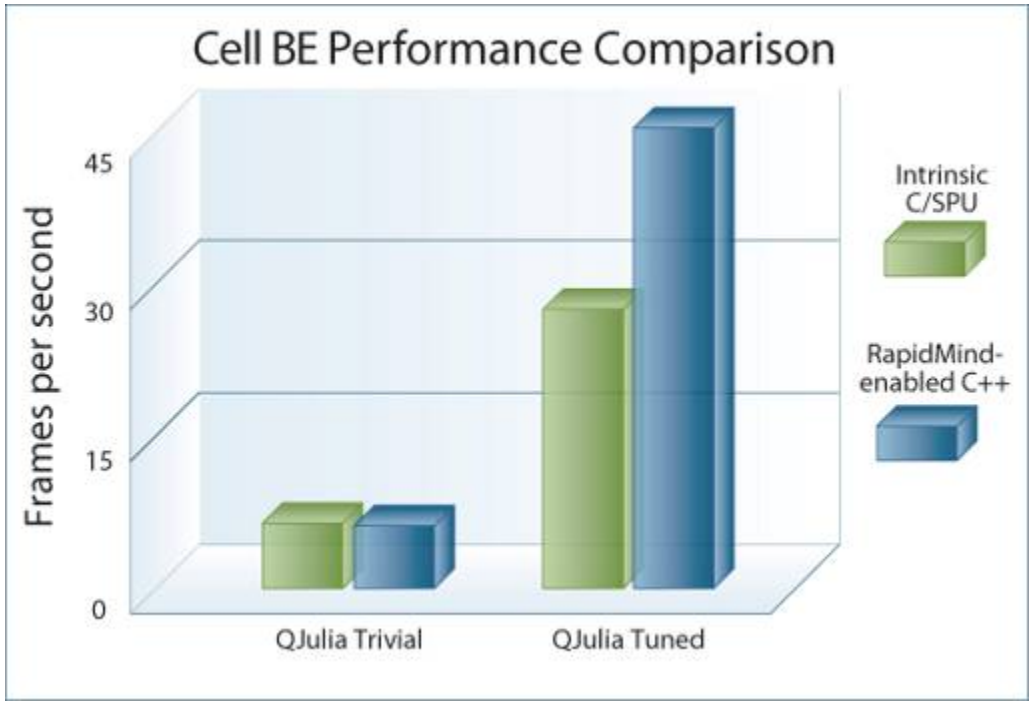
Programmability

- Use ***existing*** ISO standard C++ compiler:
  - Just include a header file, link to a library
  - Single-source solution, can be used with existing code bases
  - Does ***not*** require modification of debugging and build environments
- Allows specification of ***arbitrary computation***:
  - ***NOT*** just a library of canned functions
  - Uses its own runtime optimizing code generator
  - User can specify ***arbitrary*** computational kernels
  - Staged compilation strategy avoids overhead of C++

Portability

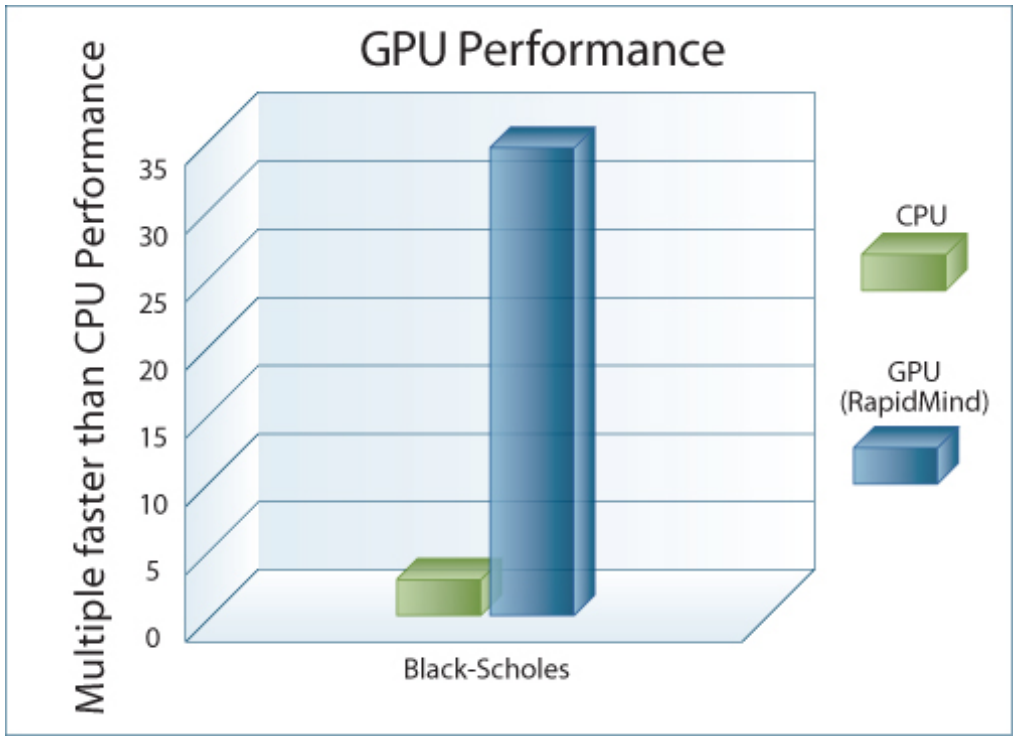
- Multiple hardware targets:
  - NVIDIA GPUs
  - AMD/ATI GPUs
  - Cell BE
  - Prototype for x86 multi-core demonstrated
- Independent of number of cores
- Independent of memory model
  - Shared or distributed
- Can support new co-processor or accelerator without even recompiling program!

Cell BE Performance



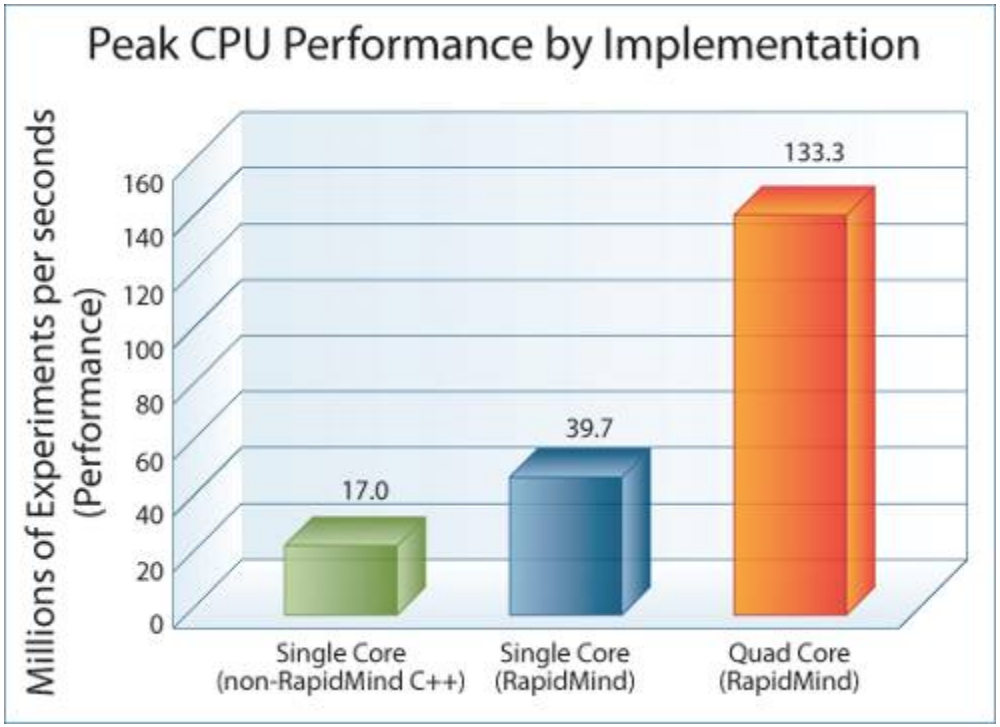
- QJulia application
- Compared with previous IBM SDK implementation
- IBM implementation released over several months
- RapidMind implementation done in a few hours
- ***Comparable or superior performance to IBM SDK implementation***
- ***Overall code size and complexity significantly lower than that of IBM SDK implementation***
- ***RapidMind version is portable to other processors***

GPU Performance



- Financial quasi Monte-Carlo option-pricing benchmark done in “competition” with HP
- CPU code uses icc autovectorization; tuned by HP, running on single Woodcrest core
- GPU implementation on an NVIDIA 7900GTX
- ***GPU implementation over 32x faster than single-core CPU implementation***

CPU Performance



- Same financial quasi Monte-Carlo option-pricing benchmark as for GPU benchmark
- RapidMind implementation basically the same as the GPU implementation
- Prototype backend targeting Intel quad-core
- ***RapidMind over 2x faster on one core, 8x faster on four cores***

Q: Library or Language?
A: *YES*

- A C++ Library API
  - For specifying arbitrary parallel computation
- A parallel programming language
  - Embedded inside C++

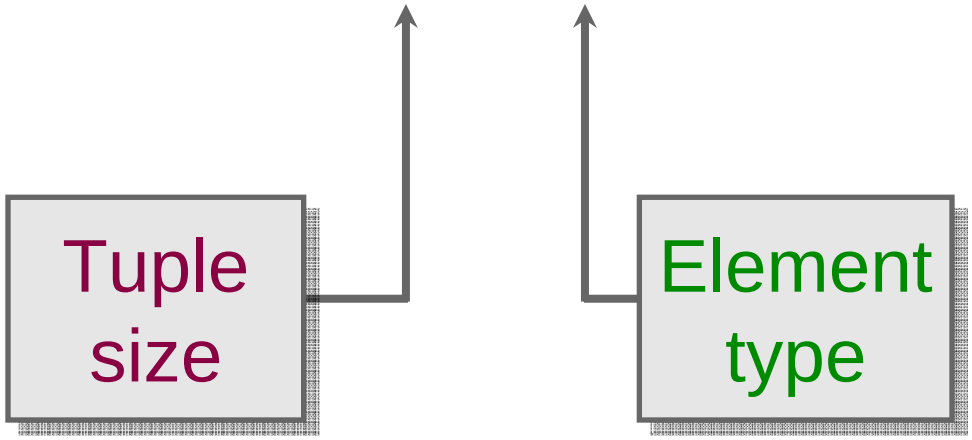
- ***Vocabulary*** for parallel programming
  - Set of nouns (types) and verbs (operations)
  - *Added* to existing standard language: ISO C++

Nouns: Basic Types

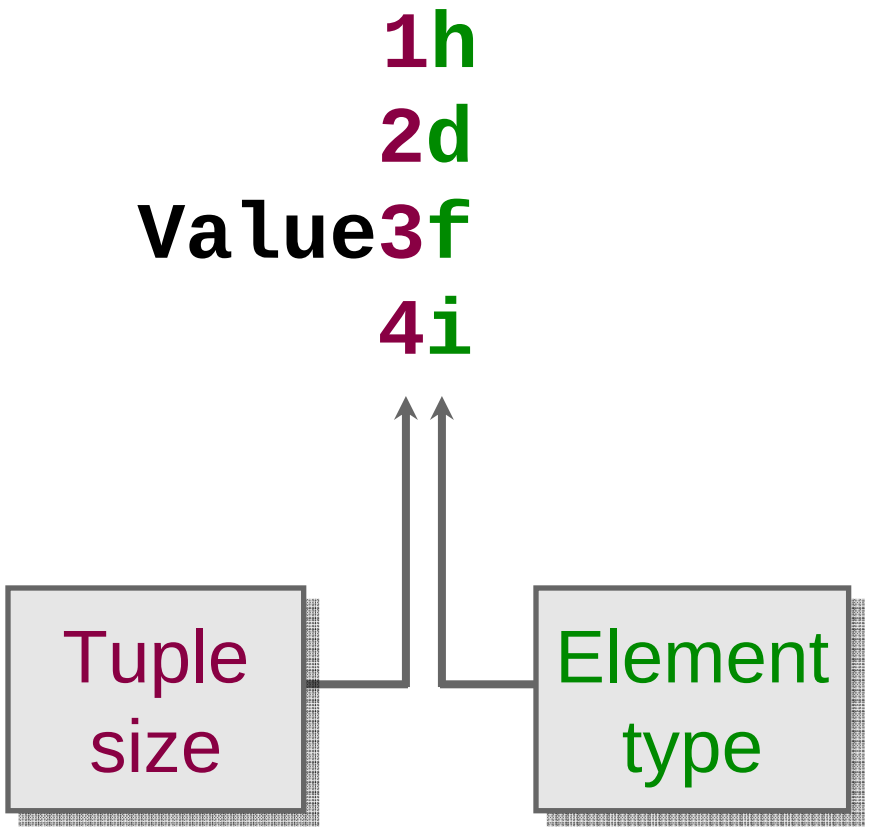
Purpose	Type
Container for fixed-length data	`Value`
Container for variable-sized multidimensional data	`Array`
Container for computations	`Program`

Values

```
          1   half
          2   double
Value<3,      float>
          4   int
```



Values



Verbs: Operators

- Operators:

```
+, -, *, /, %, &, |, ^, <, . . .
```

- Swizzling and writemasking:

```
Value4f c;
c(2,1,0)
c(0,0,0)
c(1,1,2,3)
c[3]
```

Verbs: Functions

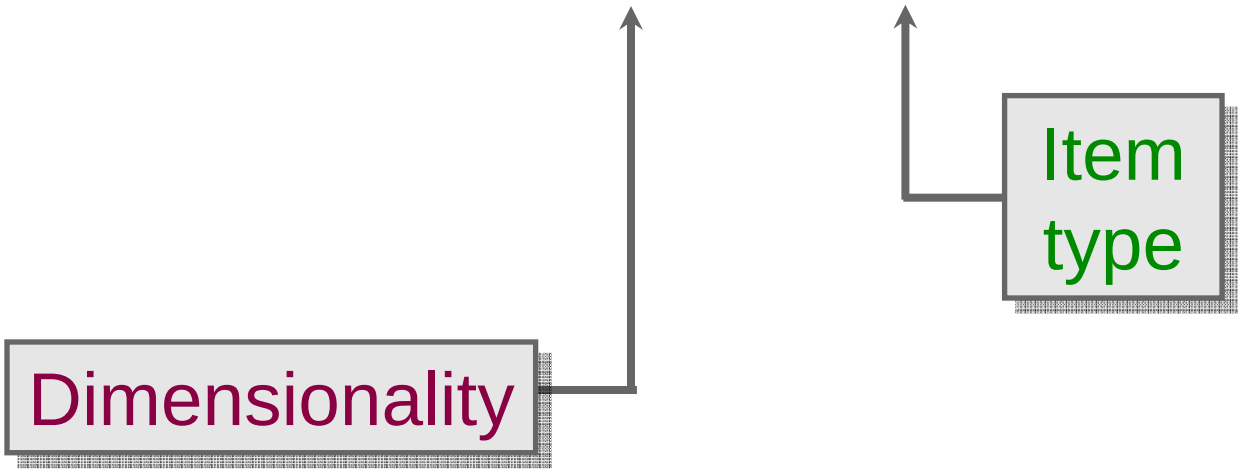
- Can declare functions in the usual way:

```
Value3f
reflect (Value3f v, Value3f n) {
    return Value3f(2.0*dot(n,v)*n - v);
}
```

- Standard library
  - Matrix operations
  - Geometric operations
  - Trigonometry
  - Exponentials and logarithms
  - Splines, interpolation, and polynomials
  - etc.

Arrays

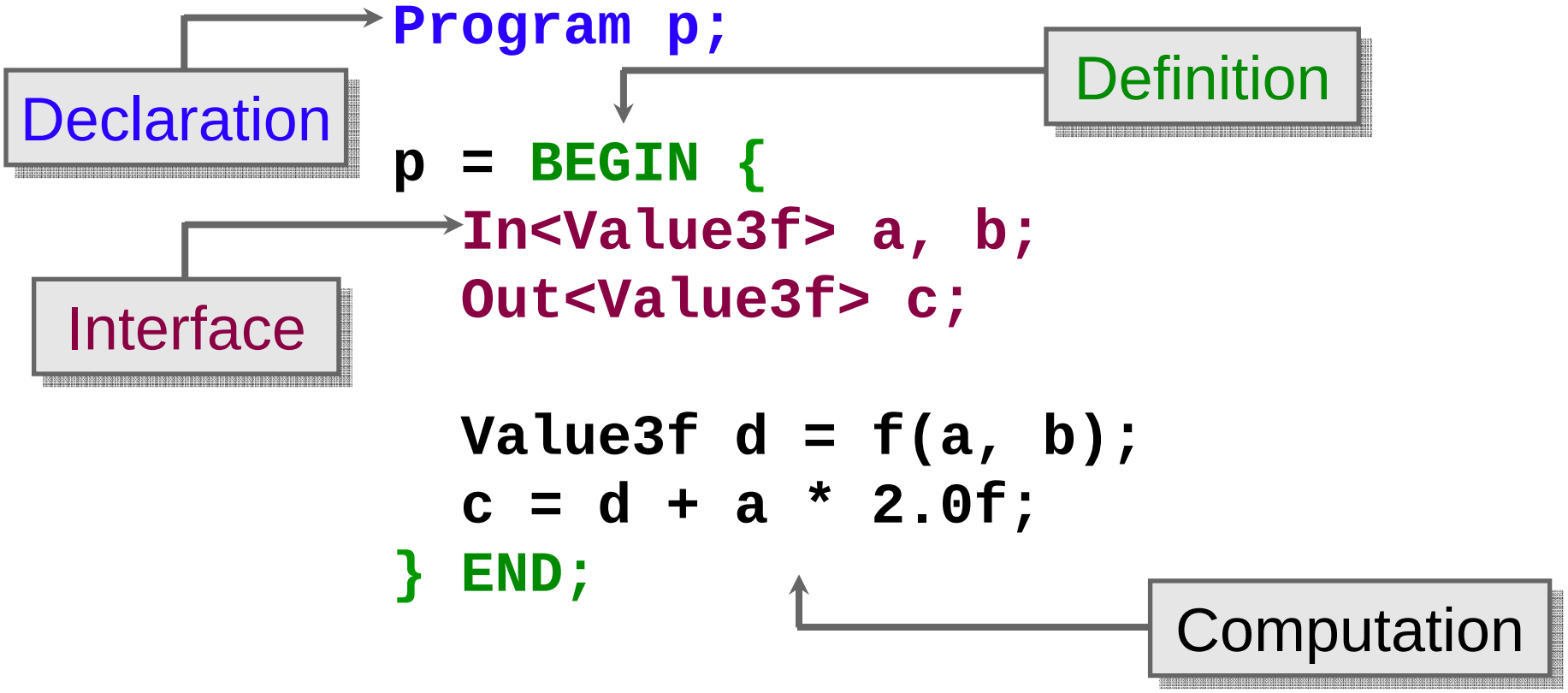
```
          1 Value4d
Array<2,Value3f>
          3 Value2i
```



Array Semantics

- Arrays use by-value semantics
  - Can assign arrays with O(1) cost
  - Strong modularity
  - Simple and easy to understand
  - Avoids needs for pointers to arrays
  - Consistent with value tuples
- Most data copies are optimized away
  - Exploits parallel assignment semantics
- By-reference semantics available:
  - **`Accessor`** type reference or “view” of region

Program Definition



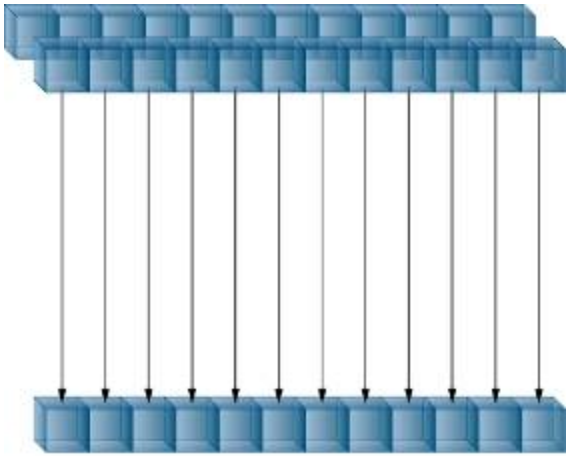
Program Application

- Apply programs to arrays, get new arrays

```
C = p(A,B);
```

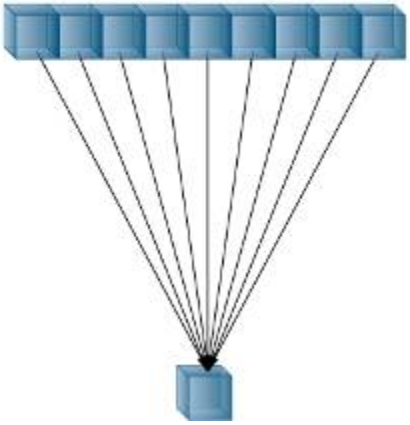
Invokes parallel execution

SPMD Data Parallel Programming Model



Apply functions to arrays:

- Application: `C = f(A,B)`
- May have control flow (SPMD model)
- May perform random reads from other arrays
- Can read and write to subarrays



Apply collective operations to arrays:

- Reduce: `a = reduce(p,A)`
- Gather: `A = B[U]`
- Scatter: `A[U] = B`
- *Others…*

Control Flow

```
Program p;

p = BEGIN {
  In<Value3f> a, b;
  Out<Value3f> c;

  Value3f d = f(a, b);
  IF (all(a > 0.0f)) {
    c = d + a * 2.0f;
  } ELSE {
    c = d – a * 2.0f;
  } ENDIF;
} END;
```

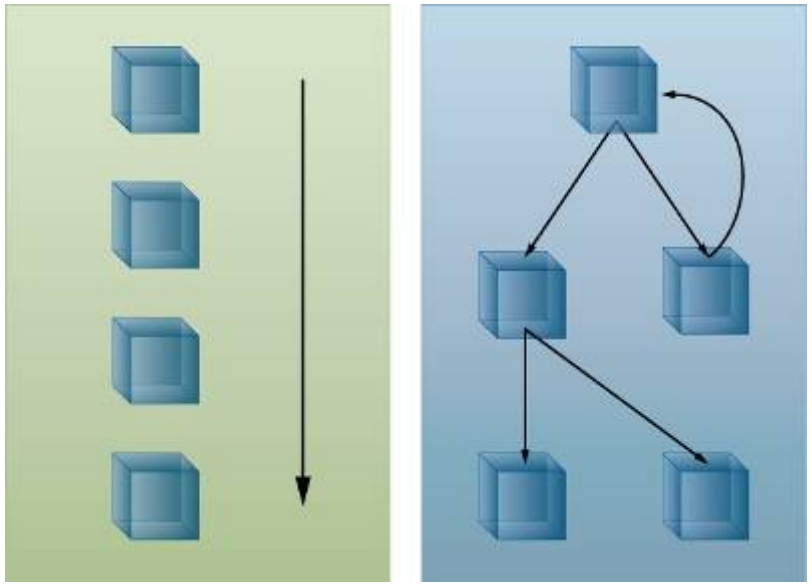
Control Flow: SPMD vs. SIMD

SIMD:

- ***Single Instruction, Multiple Data***
- Kernels include sequences of simple instructions
- Take constant amount of time to execute

SPMD:

- ***Single Program, Multiple Data***
- Kernels may include control flow (loops and conditionals)
- Can avoid unnecessary work



SIMD SPMD

SPMD includes but is *intrinsically* more powerful than SIMD

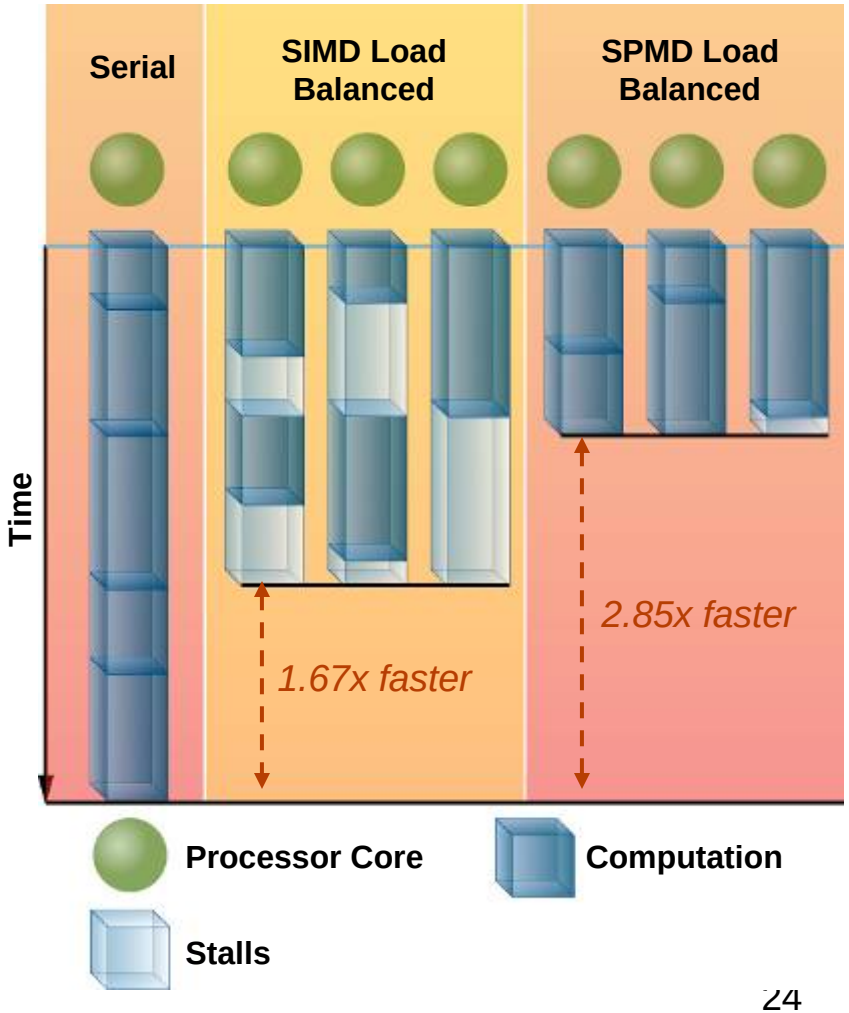
Load Balancing

SIMD scheduling

- Assumes constant time per kernel

SPMD scheduling

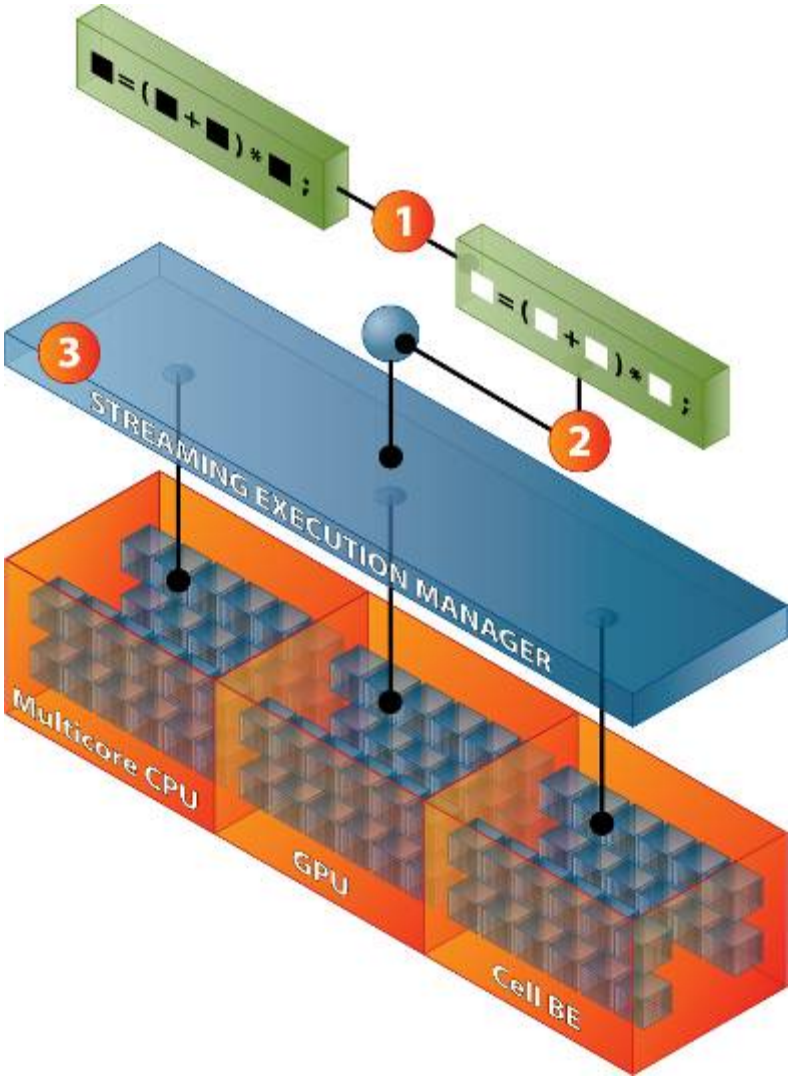
- Takes variable execution time into account
- Load balancing distributes workload evenly across cores



Loop Conversion Example

Conversion:

1. Replace Types
2. Capture Computation
3. Parallel Execution



Loop Conversion Example

```
#include <cmath>

float f;
float a[512][512][3];
float b[512][512][3];

for (int x = 0; x<512; x++) {
  for (int y = 0; y<512; y++) {
    for (int k = 0; k<3; k++) {
      a[y][x][k] = f *
        (a[y][x][k] + b[y][x][k]);
    }
  }
}
```

```
#include <rapidmind/platform.hpp>
using namespace rapidmind;
```

RAPIDMIND

1. Replace Types

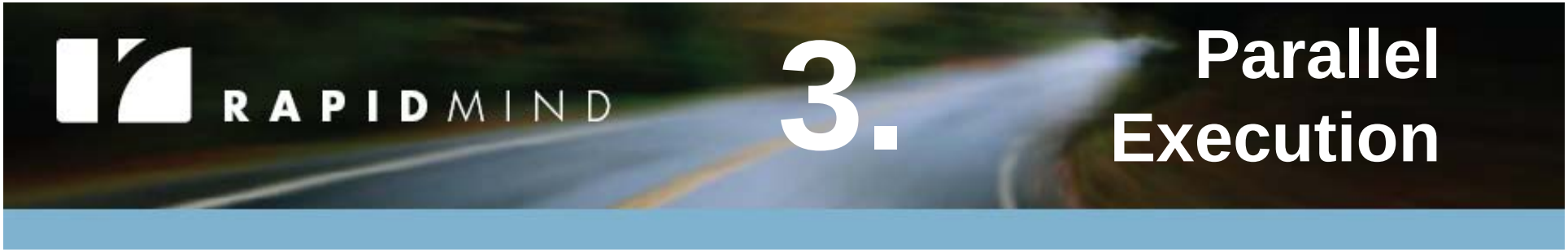
```
#include <cmath>

float f;
float a[512][512][3];
float b[512][512][3];

for (int x = 0; x<512; x++) {
  for (int y = 0; y<512; y++) {
    for (int k = 0; k<3; k++) {
      a[y][x][k] = f *
        (a[y][x][k] + b[y][x][k]);
    }
  }
}
```

```
#include <rapidmind/platform.hpp>
using namespace rapidmind;

Value1f f;
Array<2,Value3f> a(512,512);
Array<2,Value3f> b(512,512);
```

2. Capture Computations

```
#include <cmath>

float f;
float a[512][512][3];
float b[512][512][3];

for (int x = 0; x<512; x++) {
  for (int y = 0; y<512; y++) {
    for (int k = 0; k<3; k++) {
      a[y][x][k] = f *
        (a[y][x][k] + b[y][x][k]);
    }
  }
}
```

```
#include <rapidmind/platform.hpp>
using namespace rapidmind;

Value1f f;
Array<2,Value3f> a(512,512);
Array<2,Value3f> b(512,512);

Program prog = BEGIN {
  In<Value3f> r, s;
  Out<Value3f> q;
  q = f * (r + s);
} END;
```




```
#include <cmath>

float f;
float a[512][512][3];
float b[512][512][3];

for (int x = 0; x<512; x++) {
  for (int y = 0; y<512; y++) {
    for (int k = 0; k<3; k++) {
      a[y][x][k] = f *
        (a[y][x][k] + b[y][x][k]);
    }
  }
}
```

```
#include <rapidmind/platform.hpp>
using namespace rapidmind;

Value1f f;
Array<2,Value3f> a(512,512);
Array<2,Value3f> b(512,512);

Program prog = BEGIN {
  In<Value3f> r, s;
  Out<Value3f> q;
  q = f * (r + s);
} END;

a = prog(a,b);
```

Summary

Usage:

- Include platform header
- Link to runtime library

Data:

- Tuples
- Arrays
- *Global data abstraction*

Programs:

- Defined dynamically
- Safe parallel execution
- *Remote procedure abstraction*

```
#include <rapidmind/platform.hpp>
using namespace rapidmind;

Value1f f;
Array<2,Value3f> a(512,512);
Array<2,Value3f> b(512,512);

Program prog = BEGIN {
  In<Value3f> r, s;
  Out<Value3f> q;
  q = f * (r + s);
} END;

a = prog(a,b);
```

Debugging

- Can just use existing IDE
- Single-step through code in immediate mode
- RapidMind control flow DOES work outside of program definitions (in “immediate mode”)

Profiling and Performance Tuning

- Program objects can provide reports on performance
- Program objects can output optimized, annotated code
- Mechanisms available to attach annotations to code
- Synchronization mechanism for accurate timing
- Compilation logs can warn of use of features that are inefficient for particular hardware targets

Summary

- Provides abstractions for *both* code *and* data
  - Use C++ modularity, but compile out overhead
- Multiple hardware targets
  - GPU
  - Cell BE
  - Multi-core CPUs demonstrated and under development
- Simple, safe programming model
  - Avoids race conditions, deadlock, non-determinism
- Can achieve outstanding performance and productivity
  - Minimize training, effort, and risk
  - Maximize return on investment
- Single-source ISO standard C++ program:
  - ***No extensions or preprocessor needed***
  - ***Works with existing compilers***

Sample Applications

Examples

- Crowd simulation
- Ray tracing (by RTT, in shipping product)
- Fast Fourier transform
- Convolution
- Quasi Monte Carlo option pricing
- Matrix-matrix multiply (SGEMM)
- Transformation and lighting
- Color and gamma correction
- Object tracking
- Sorting
- Set intersection (used for keyword search)
- Deferred shading
- Solution of partial differential equations
- *Others…*

Crowd Simulation

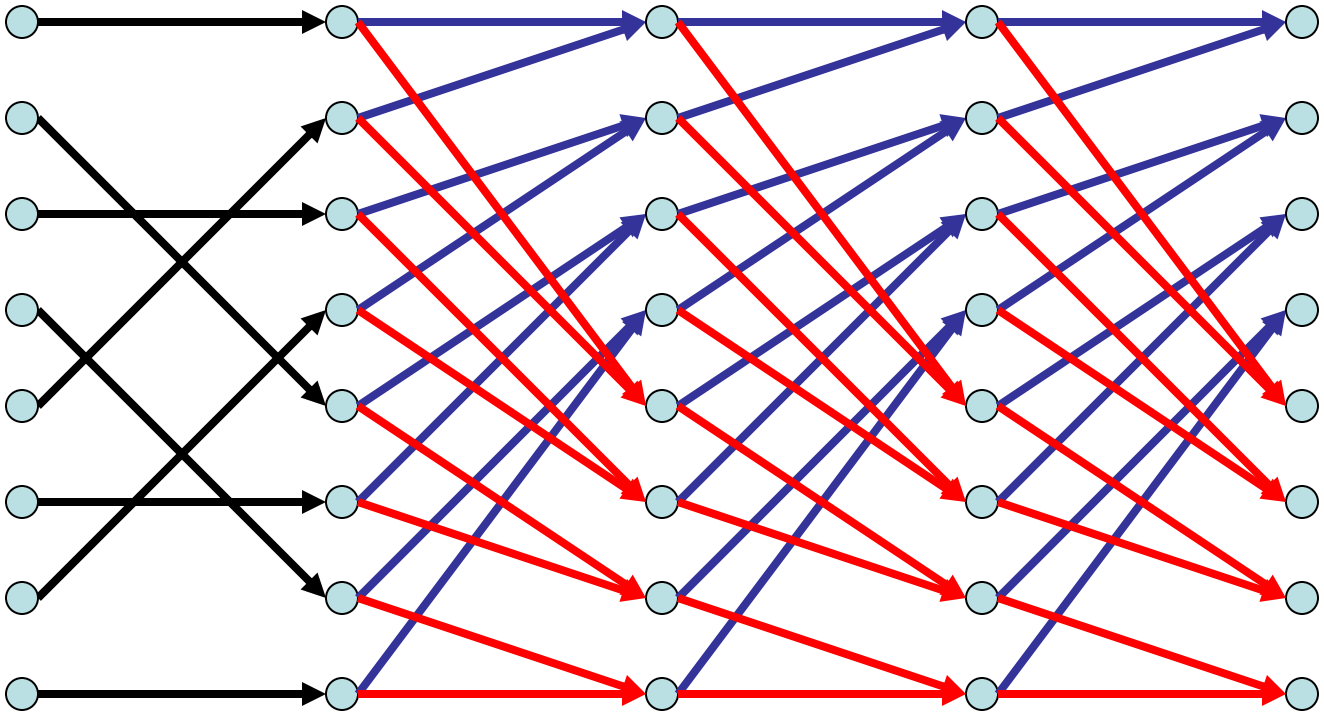
Crowd Simulation

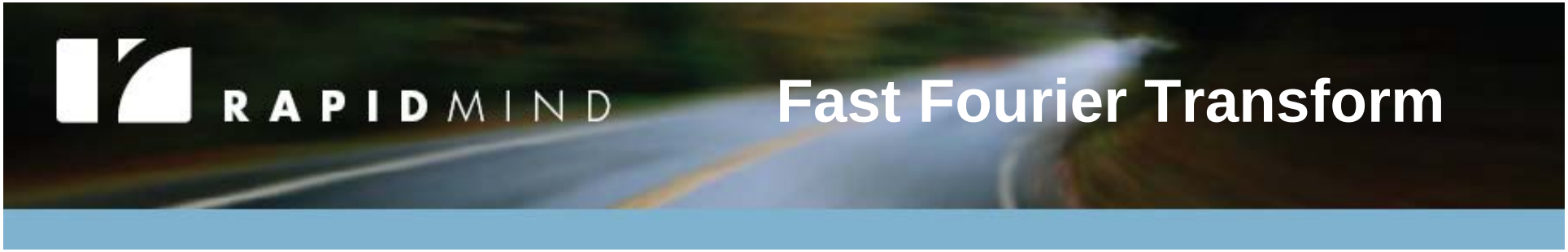
- Graphics on GPU
  - Shaders ***also*** implemented using RapidMind platform
- Behavioral Simulation on Cell BE Blade
  - 16K autonomous characters (4K visible at once)
- Parallel Execution:
  - Rules to simulate social behavior and basic physics
- Global Communication:
  - Any character can interact with any other
    - Requires (approximate) solution to K-nearest-neighbor problem
  - Behavior depends on the environment
    - Random access to environmental parameter grid
    - Obstacles, ground cover and slope

Fast Fourier Transform

- Fundamental signal processing operation
  - Image processing
  - Pattern matching
  - Solving differential equations
- Standard test case for parallel computation
- Involves both
  - Computation
  - Communication
- Many varieties and ways to implement
  - Will show radix-2 split-stream complex-to-complex 1D FFT

Signal Flow Graph






```
// Fast Fourier Transform
Array<1,Value2f>
FFT (Array<1,Value2f> data, int n) {
    int N = (1 << n);

    // define program objects
    …

     // generate and scramble twiddle factors with gather
    …

    // scramble input data using a gather
    …

    // perform split-stream FFT using lg(N) passes
    …
}
```

Fast Fourier Transform

```
// define program objects
Program butterfly_A = BEGIN {
    In<Value2f> a, b;
    Out<Value2f> c = a + b;
} END;

Program butterfly_B = BEGIN {
    In<Value2f> a, b, w;
    Value2f t = a - b;
    Out<Value2f> c;
    c[0] = t[0]*w[0] + t[1]*w[1];
    c[1] = t[1]*w[0] - t[0]*w[1];
} END;
```

Fast Fourier Transform

```
// generate and scramble twiddle factors with gather
Array<1,Value2f> w(N/2);
w = twiddle(n-1)[ bitreverse(n-1) ];

// allocate temporary storage
Array<1,Value2f> x[2];
x[0] = Array1D<Value2f>(N);
x[1] = Array1D<Value2f>(N);

// scramble input data using a gather
x[0] = data[ bitreverse(n) ];

// initialize source marker
int src = 0;
```

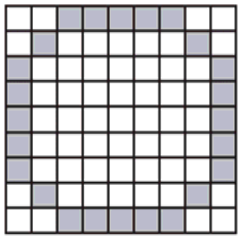
Fast Fourier Transform

```
// perform split-stream FFT using log(N) passes
for (int k=n-1; k>=0; k--) {
    // write into lower half of output array
    take(x[!src],N/2) = butterfly_A(
      stride(x[src],2),
      stride(offset(x[src],1),2)
    );
    // write into upper half of output array
    offset(x[!src],N/2) = butterfly_B(
      stride(x[src],2),
      stride(offset(x[src],1),2),
      take(w,1<<k)
    );
    // swap source and destination buffers
    src = !src;
}
// return final transform
return x[src];
```

Convolution

- Fundamental signal processing operation
- For large filters, use FFT
  - FFT
  - Elementwise complex multiplication
  - Inverse FFT
- For small filters, do directly
  - Shift flipped filter to each pixel, multiply, sum
  - May process many images with one filter
  - Filters used in pattern matching may be sparse
  - Can exploit sparsity to get more efficient execution

Convolution



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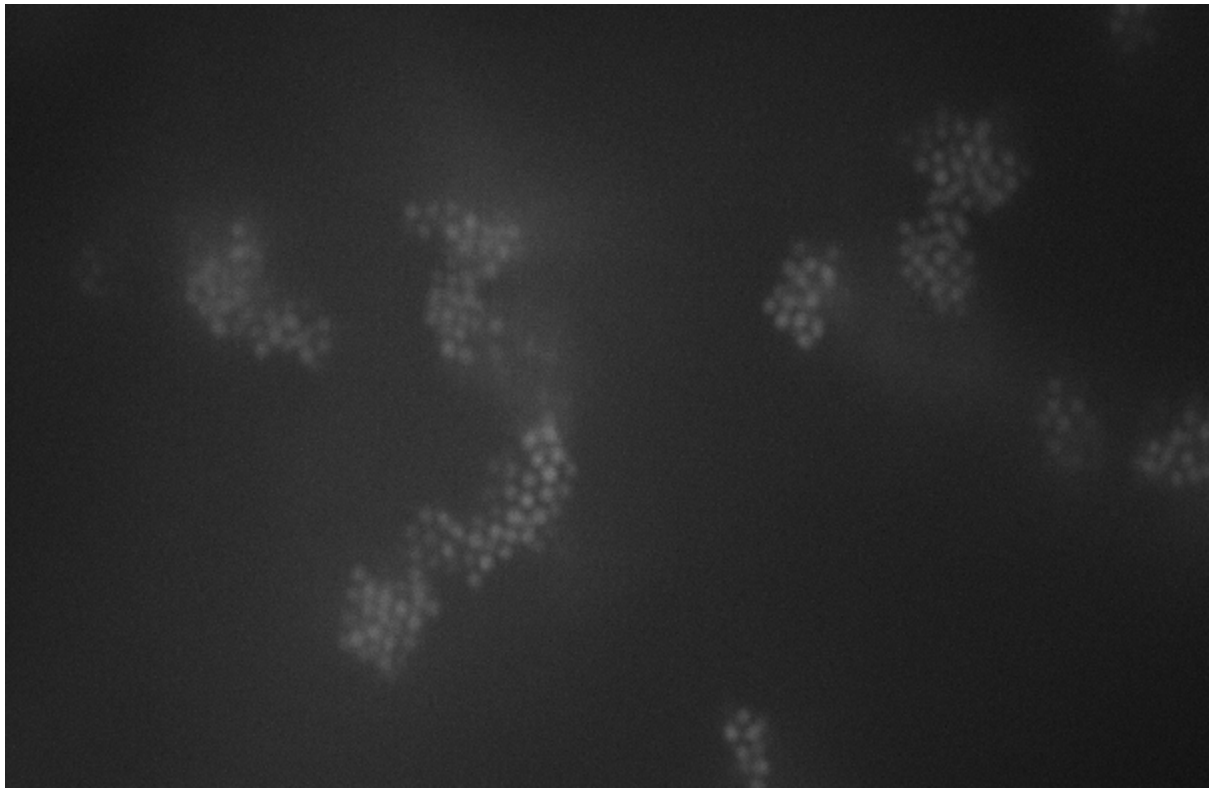

Confocal microscopy image
courtesy of Peter J. Lu, Harvard

Convolution

```
float filter[N0][N1];
Array<2,Value1f> image(M0,M1);

Program convolve = BEGIN {
  In<Value2i> u;
  Out<Value1f> result = Value1f(0.0f);
  for (int i = 0; i < N0; i++) {
    for (int j = 0; j < N1; j++) {
      if (filter[i][j] != 0.0f) {
        Value2i tap = u - Value2i(i,j);
        result += filter[i][j] * image[tap];
      }
    }
  }
} END;

image = convolve(grid(M0,M1));
```

Raytracing

- Real-time raytracing
  - Supports reflection and refraction
  - Many recursive rays per pixel
  - Approximately 15Hz on real CAD data
- Commercial product:
  - Developed by RTT AG, Germany
  - Used for automotive CAD visualization
  - ***Shipping product***
- Hardware:
  - Released product runs on NVIDIA GPUs on HP workstations
  - Demonstrated on Cell BE at SIGGRAPH 2006

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Raytracing