Ct: A New Paradigm for Data Parallel Computing
Hans-Christian Hoppe
Intel Visual Computing Institute, Intel Labs

using material from

Anwar Ghuloum, CJ Newburn, Michael McCool and Stefanus Du Toit
Performance and Productivity Libraries, Developer Products Division, Software and Services Group

Contents
Ct 101
– What is Ct, and what value does it provide?
– Basic language elements and examples

Ct Next Steps – Where to go from here
– Towards a parallel virtual machine

How to learn more

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Challenge: Multiple Parallelism Mechanisms

Today’s parallel platforms have many kinds of parallelism:
– Pipelining
– SIMD within a register (SWAR) vectorization
– Superscalar instruction issue or VLIW
– Overlapping memory access with computation (prefetch)
– Simultaneous multithreading (hyperthreading) on one core
– Multiple cores
– Multiple processors
– Asynchronous host and accelerator execution
**Automatically Select the Right Mechanisms**

Solution: take a single abstract specification of latent parallelism and data locality and use automation to transform it into multiple implementations that can exploit all these mechanisms.

User specifies:

Platform implements:

Example implementation uses:
- Two cores
- Four-way vectorization
- Memory latency hiding with streaming

Actual distribution of work depends on hardware

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**What is Ct Technology?**

- A generalized data parallel programming solution that frees application developers from dependencies on particular hardware architectures.
- A system that integrates with existing development tools to allow parallel algorithms to be specified at a high level.
- A dynamic compiler and runtime that translates high-level specifications of computations into efficient parallel implementations that can take advantage of both SIMD and thread-level parallelism, as well as accelerators.
- **A system that allows an application developer to combine performance, portability, and productivity.**

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**What value does it provide?**

**Productivity**
- Integrates with existing tools
- Applicable to many problem domains
- Safe by default: maintainable

**Performance**
- Efficient and scalable
- Harnesses both vectors and threads
- Eliminates modularity overhead of C++

**Portability**
- High-level abstraction
- Hardware independent
- Forward scaling

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**The Ct Runtime**

- Intel Ct Technology offers a standards compliant C++ library... ...backed by a runtime

- Runtime generates and manages threads and vector code, via
  - Machine independent optimization
  - Offload management
  - Machine specific code generation and optimizations
  - Scalable threading runtime (based on TBB!)

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Software & Services Group, Developer Products Division

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What can it be used for?

**Visual computing**
- Digital content creation (DCC)
- Physics engines and advanced rendering
- Visualization
  - Compression/decompression
  - Microscopy and satellite image processing

**Science and research**
- Machine learning and artificial intelligence
- Climate and weather simulation
- Planetary exploration and astrophysics

**Engineering design**
- Finite element and finite difference simulation
- Monte Carlo simulation
- Radar and sonar processing
- Microscopy and satellite image processing

**Medical imaging**
- Image and volume reconstruction
- Analysis and computer-aided detection (CAD)

**Signal and image processing**
- Computer vision
- Radar and sonar processing
- Microscopy and satellite image processing

**Bioinformatics**
- Genomics and sequence analysis
- Molecular dynamics

**Engineering design**
- Finite element and finite difference simulation
- Monte Carlo simulation

**Oil and gas**
- Seismic reconstruction

**Medical imaging**
- Image and volume reconstruction
- Analysis and computer-aided detection (CAD)

**Data Spaces**

C/C++ space          Ct space

\[ vec + vec = vec \]

**Ct Language Introduction**

**Ct Data Objects**

The basic type in Ct is the vector, named as Vec

- Vecs are managed by the Ct runtime
- Vecs are single-assignment vectors
- Vecs are (opaquely) flat, multidimensional, sparse, or nested
- Vec values are created & manipulated exclusively through Ct API

Declared Vecs are simply references to immutable values

```c
Vec<F64> doubleVec; // doubleVec can refer to any vector of doubles
...
doubleVec = src1 + src2;
...
doubleVec = src3 * src4;
```
Moving Data In and Out of Ct

Bind data with Ct name using Vec constructors

Vec<F32> prices(options, numOptions); // copy in from a C array
Vec<IB> redImage, length, 4); // copy element with a stride of 4
Vec2D<IB> intVec(rows, width, height); // A vector initialized to all -1s

Define the data behavior in the kernel’s signature

- Pass-by-value – means copying in
- Pass-by-reference – means both copying in and copying out
- Dynamic Compiler tries to recognize pure copying out

Ct Operators - Vector Element-wise operators

Unary Operators
A = ~B; // bitwise not of each element of B
A = exp(B); // compute the exp() of each element of B

Binary Operators
A = B + C; // an element-wise sum of B & C
D = max(E, F); // an element-wise maximum of E and F
G = 2*H; // element-wise multiplication of H and the scalar 2

Ternary Operators
A = select(mask, B, C);
A = select(mask, B, 0.f);

Ct Operators - Vector Reduce / Scan

Reductions (e.g. aggregation, collective communication)

// Sum all the element of B
A = addReduce(B);
// Some common cases for BOOLEAN
Vec<Bool> B;
//TRUE if all elements of B are TRUE
Bool alltrue = all(B);
//TRUE if at least one element of B is TRUE
Bool nonzero = any(B);

Scans
// calculate the prefix sum of B
A = addScan(B);

Ct Operators - Vector Permutation Operators

Shift
A = shift(B, 1);
A = shiftSticky(B, 1);

Rotate
A = rotate(B, 1);

Gather / Scatter
A = B [vindex];
A = scatter(B, vindex, C);
A Simple Example: Dot Product

Dot Product Using C Loops

```c
for (i = 0; i < n; i++) {
    dst += src1[i] * src2[i];
}
```

Vector operations subsumes loop

Element-wise multiply

Reduction (a global sum)

A More Complex Example: Porting Black-Scholes

Black-Scholes Using C Loops

```c
void BlackScholes(Vec<F32> in, Vec<F32>& out1, Vec<F32>& out2) {
    Vec<F32> d1 = s / ln(X);
    d1 += (R + V * V * 0.5f) * T;
    d1 /= sqrt(T);
    Vec<F32> d2 = d1 - s / sqrt(T);
    result *= exp(-d2 * d2); // output
}
```

Include `<ct.h>` and use Ct namespace

Vector operations subsumes loop

The Ct code is almost the same as the original loop body

Functions

- A Ct Function is a C++ function that
  - takes one or more Vec, Elt (a Vec element), or scalars as arguments
  - returns one or more Vec, Elt (a Vec element), or scalars
    - one return: `Vec<F32> foo(Vec<F32> in);`
    - two returns: `void foo(Vec<F32> in, Vec<F32>& out1, Vec<F32>& out2);`
  - is invoked via special interfaces:
    - `call/rcall`
    - `map/rmap`
    - `ncall/nmap` (internal-only, for now)

Remote calls: Invoke Functions from C/C++ Space

```c
void BlackScholes(Vec<F32> in, Vec<F32> out) {
    Vec<F32> d1 = s / ln(X);
    d1 += (R + V * V * 0.5f) * T;
    d1 /= sqrt(T);
    Vec<F32> d2 = d1 - s / sqrt(T);
    result *= exp(-d2 * d2); // output
}
```

For functions that are remotely invoked, the return values have to be expressed using pass by ref operator, and the functions MUST return void.

//c caller code
```c
void foo(Vec<F32> in, Vec<F32>& out1, Vec<F32>& out2);
```
Ct Dynamic Engine Execution

```c
int ar_a[1024], ar_b[1024]
Vec<I32> va(ar_a, ...);
Vec<I32> vb(ar_b, ...);
rcall(work)(va, vb);
```

Memory Manager

```c
void work(Vec<I32> a, Vec<I32>& b)
{
    b = a + 1;
}
```

IR Builder
Towards a Parallel Virtual Machine

```c
int ar_a[1024], ar_b[1024]
Vec<I32> va(ar_a, ...);
Vec<I32> vb(ar_b, ...);
rcall(work) (va, vb);
```

```c
void work(Vec<I32> a, &b) {
  Kernel b = a + 1;
  Again
}
```
Parallel Programming Abstractions

- C++
- Java
- .NET
- Python
- ... (High-level, programming language)

- Ct
- TBB
- Emerging Parallel Languages...

- Threads
- Concurrency

Industry gap in "parallel VM"

Parallel VM Tasks

- Provide function definition, data management and execution
- Decouple programming languages from concurrency platforms
  - Allowing new frontends to flourish
- Be well-defined, offer C API and textual representation
  - Suitable for wide external adoption

Evolve Ct into Data-parallel Virtual Machine

- Converge Ct and RapidMind APIs into open, standard VM layer
- Goals:
  - New frontends for other languages (e.g., .NET, Python, Java, etc.)
  - Enable domain specific languages
  - Leverage data-parallel execution engines from Intel
  - Provide interface specification for non-Intel implementations
  - Clearly specify semantics separately from syntax
  - Binary compatibility and insulation
- Not generally aimed at application developers

- Collaboration welcome!
  - Email to stefanus.du.toit@intel.com!

Ct In–Depth Information and Product Plans
Ct Going Forward

• Ct is being turned into an Intel software product
  – public beta release planned for Q1/2010
• The product will contain
  – Core API
  – Libraries for Linear Algebra, FFT, Random Number Generation (powered by Intel® Math Kernel Library)
  – Lots of samples (Medical Imaging, Financial Analytics, Seismic Processing, ...)
• Initial release on Windows, followed by Linux
  – IA-32 and Intel® 64 instruction sets
  – Works with Intel® C/C++ Compiler, Microsoft® Visual C++®, and GCC*
  – Works with Intel® VTune™ Analyzer

How to Learn More about Ct

• Read the material at [http://www.intel.com/go/ct](http://www.intel.com/go/ct)
• Browse the Intel Developer Forum website for Ct presentations
• Bug your favorite Intel rep about getting into the private beta program
• Sign up for the public beta at [http://www.intel.com/go/ct](http://www.intel.com/go/ct)