Efficient Mapping of Irregular C++ Applications to Integrated GPUs

Rajkishore Barik (Presenter)

Rashid Kaleem, UT Austin

Deepak Majeti, Rice University

Brian T. Lewis, Intel Labs

Tatiana Shpeisman, Intel Labs

Chunling Hu, Intel Labs

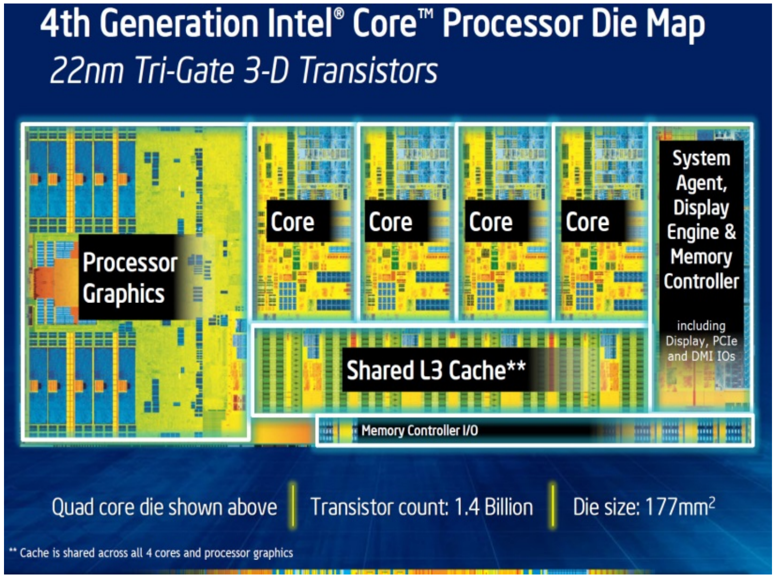
Yang Ni, Google

Ali-Reza Adl-Tabatabai, Google

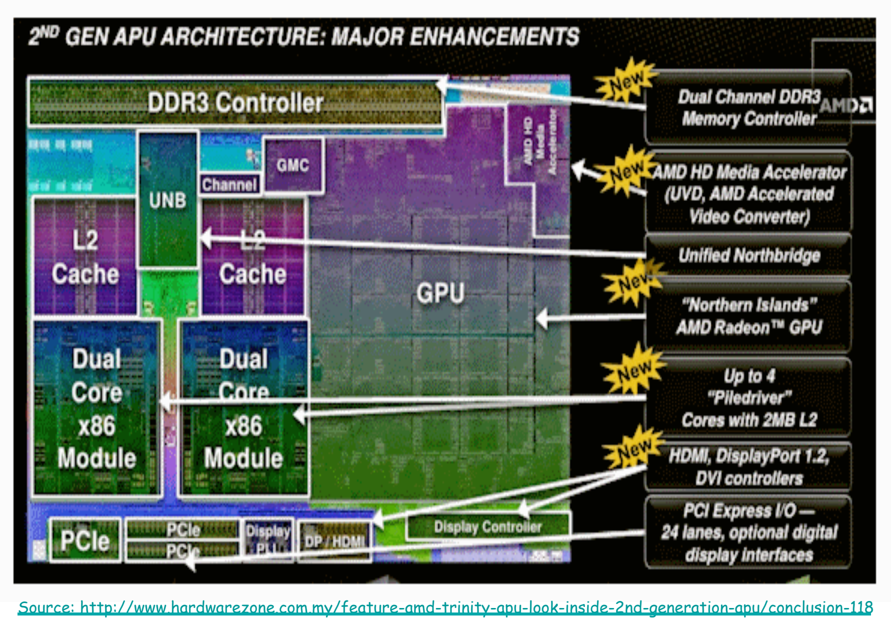
Heterogeneous Platforms

- **Heterogeneity is ubiquitous: mobile devices, laptops, servers, & supercomputers**
- **Emerging hardware trend: CPU & GPU cores integrated on same die, share physical memory & even last-level cache**

Intel 4th generation core processors



AMD Trinity



Source: http://www.hardwarezone.com.my/feature-amd-trinity-apu-look-inside-2nd-generation-apu/conclusion-118

How do we program these integrated GPU systems?

Motivation: GPU Programming

- Existing work: regular data-parallel applications using array-based data structures map well to the GPUs
  - OpenCL 1.x, CUDA, OpenACC, C++ AMP, …
- Enable other existing multi-core applications to quickly take advantage of the integrated GPUs
  - Often use object-oriented design, pointers
    - Enable pointer-based data structures on the GPU
  - Irregular applications on GPU: benefits are not well-understood
    - Data-dependent control flow
      - Graph-based algorithms such as BFS, SSSP, etc.

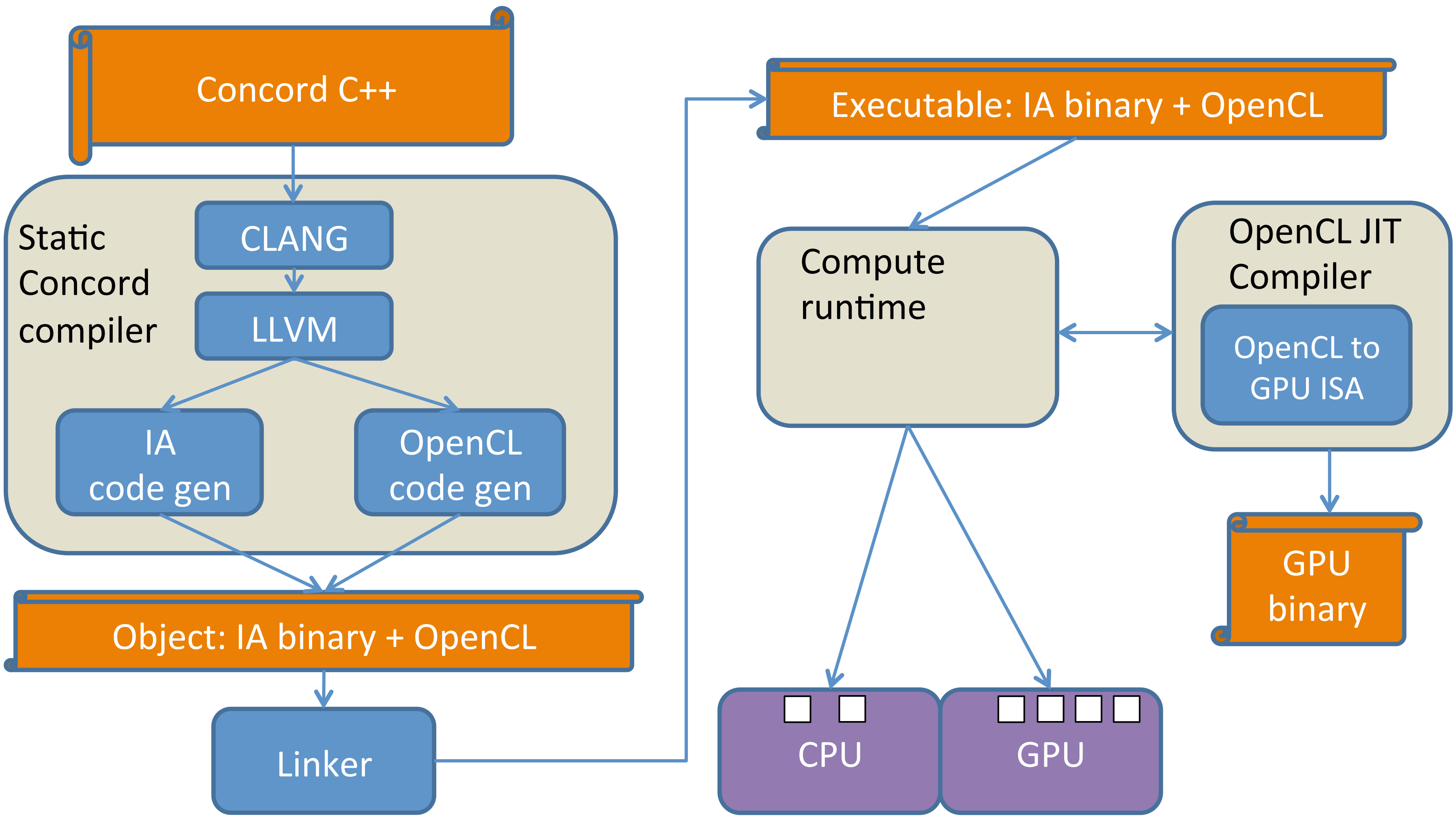
Widen the set of applications that target GPUs

Contributions

- Concord: a seamless C++ heterogeneous programming framework for integrated CPU and GPU processors
  - Shared Virtual Memory (SVM) in software
    - share pointer-containing data structures like trees
  - Adapts existing data-parallel C/C++ constructs to heterogeneous computing: TBB, OpenMP
  - Supports most C++ features including virtual functions
  - Demonstrates programmability, performance, and energy benefits of SVM

- Available open source at https://github.com/IntelLabs/iHRC/

Concord Framework



Concord C++ programming constructs

Concord extends TBB APIs:

```
template <class Body>
parallel_for_hetero (int numiters, const Body &B,
                                    bool device);

template <class Body>
parallel_reduce_hetero (int numiters, const Body &B,
                                    bool device);
```

Existing TBB APIs:

```
template <typename Index, typename Body>
parallel_for (Index first, Index last, const Body& B)

template <typename Index, typename Body>
parallel_reduce (Index first, Index last, const Body& B)
```

Supported C++ features:

- Classes
- Namespaces
- Multiple inheritance
- Templates
- Operator and function overloading
- Virtual functions

Currently not supported on GPU

- Recursion
- Exceptions
- Memory allocation

Concord C++ Example: Parallel LinkedList Search

```
class ListSearch {
…
void operator()(int tid) const{
     ... list->key...
}};
…
ListSearch *list_object = new ListSearch(…);


parallel_for(0, num_keys, *list_object);
```

TBB Version

```
class ListSearch {
…
void operator()(int tid)  const{
     ... list->key...
}};
…
ListSearch *list_object = new ListSearch(…);


parallel_for_hetero (num_keys, *list_object, GPU);
```

Run on CPU or GPU

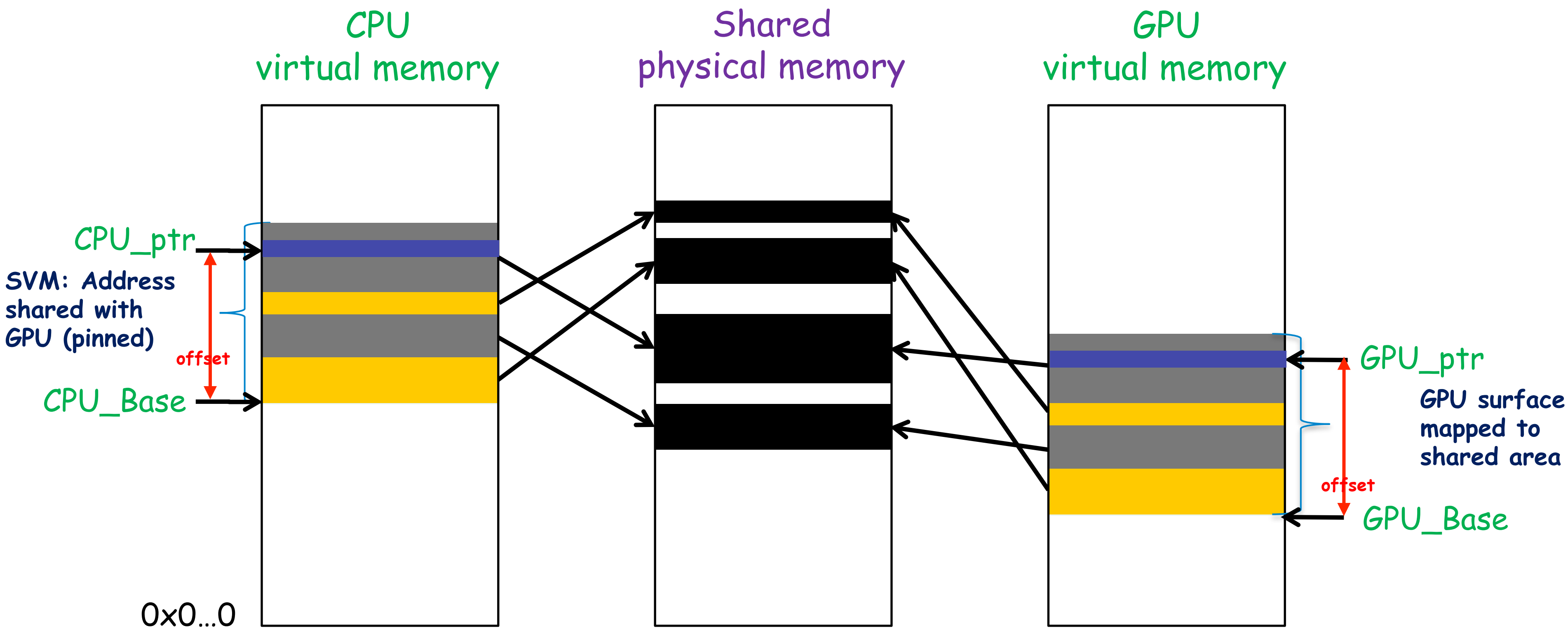
Concord Version

Minimal differences between two versions

Key Implementation Challenges

- **Shared Virtual Memory (SVM) support to enable pointer-sharing between CPU and GPU**
  - **Compiler optimization to reduce SVM translation overheads**
- **Virtual functions on GPU**
- **Parallel reduction on GPU [paper]**
- **Compiler optimizations to reduce cache line contention [paper]**

SVM Implementation on IA



GPU_ptr = GPU_Base + CPU_ptr – CPU_Base

SVM Translation in OpenCL code

```
class ListSearch {
…
void operator()(int tid)  const{
     ... list->key...
}};
…
ListSearch *list_object = new ListSearch(…);

parallel_for_hetero (num_keys, *list_object, GPU);
```

Concord C++

```
//__global char * svm_const = (GPU_Base – CPU_Base);

#define AS_GPU_PTR(T,p) (__global T *) (svm_const + p)

__kernel void opencl_operator (
        __global char *svm_const,
        unsigned long B_ptr) {

    AS_GPU_PTR(LinkedList, list)->key…
}
```

Generated OpenCL

- svm_const is a runtime constant and is computed once
- Every CPU pointer before dereference on the GPU is converted into GPU addressspace using AS_GPU_PTR

Compiler Optimization of SVM Translations

```
int **a = data->a;
for ( int i=0; i<N; i++)
  … = a[i];
// a[i] is not used after this
```

Eager

```
int **a = AS_GPU_PTR(int *, data->a);
for ( int i=0; i<N; i++)
   … = AS_CPU_PTR(int,
         AS_GPU_PTR(int, a[i]));
```

Overhead: 2N + 1

Lazy

```
int **a = data->a;
for ( int i=0; i<N; i++)
   … = AS_GPU_PTR(int *, a)[i];
```

Overhead: N

Best

```
int **a = AS_GPU_PTR(int *, data->a);
for ( int i=0; i<N; i++)
  … = a[i];
```

Overhead: 1

- **Best strategy:**
  - Eagerly convert to GPU addressspace & keep both CPU & GPU representations
  - If a store is encountered, use CPU representation
  - Additional optimizations
    - Dead-code elimination
    - Optimal code motion to perform redundancy elimination and place the translations

Virtual Functions on GPU

Original hierarchy:

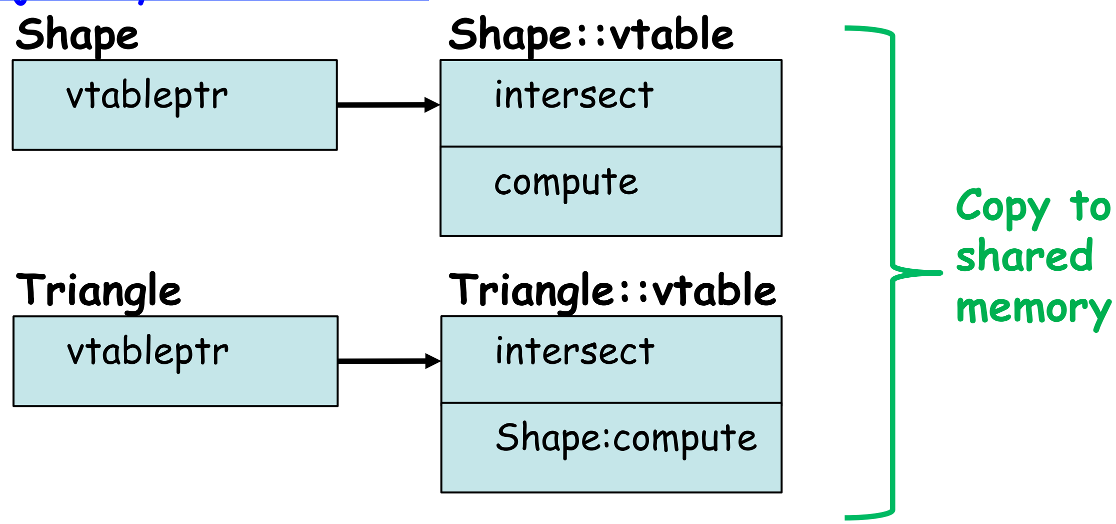
```
class Shape {
  virtual void intersect() {…}
  virtual void compute() {…}
};
class Triangle : Shape {
  virtual void intersect() {…}
};
```

Virtual Function call:

```
void foo(Shape *s) {
  s->compute();
}
```

Original code

Object layout with vtable:



CPU Virtual Function call:

```
void foo(Shape *s) {
  (s->vtableptr[1])();
}
```

GPU Virtual Function call:

```
void foo(Shape *s, void *gCtx) {
  if (s->vtableptr[1] == gCtx->
              Shape::compute)
     Shape::compute();
}
```

Generated code

- Copy necessary metadata into shared memory for GPU access
- Translate virtual function calls into if-then-else statements

Experimental setup

- **Experimental Platform:**
  - **Intel Core 4th Generation Ultrabook**
    - **CPU: 2 cores, hyper-threaded, 1.7GHz**
    - **GPU: Intel HD Graphics 5000 with 40 cores, 200MHz-1.1GHz**
    - **Power envelope 15W**
  - **Intel Core 4th Generation Desktop**
    - **CPU: 4 cores, hyper-threaded, 3.4GHz**
    - **GPU: Intel HD Graphics 4600 with 20 cores, 350MHz-1.25GHz**
    - **Power envelope 84W**

- **Energy measurements: MSR_PKG_ENERGY_STATUS**

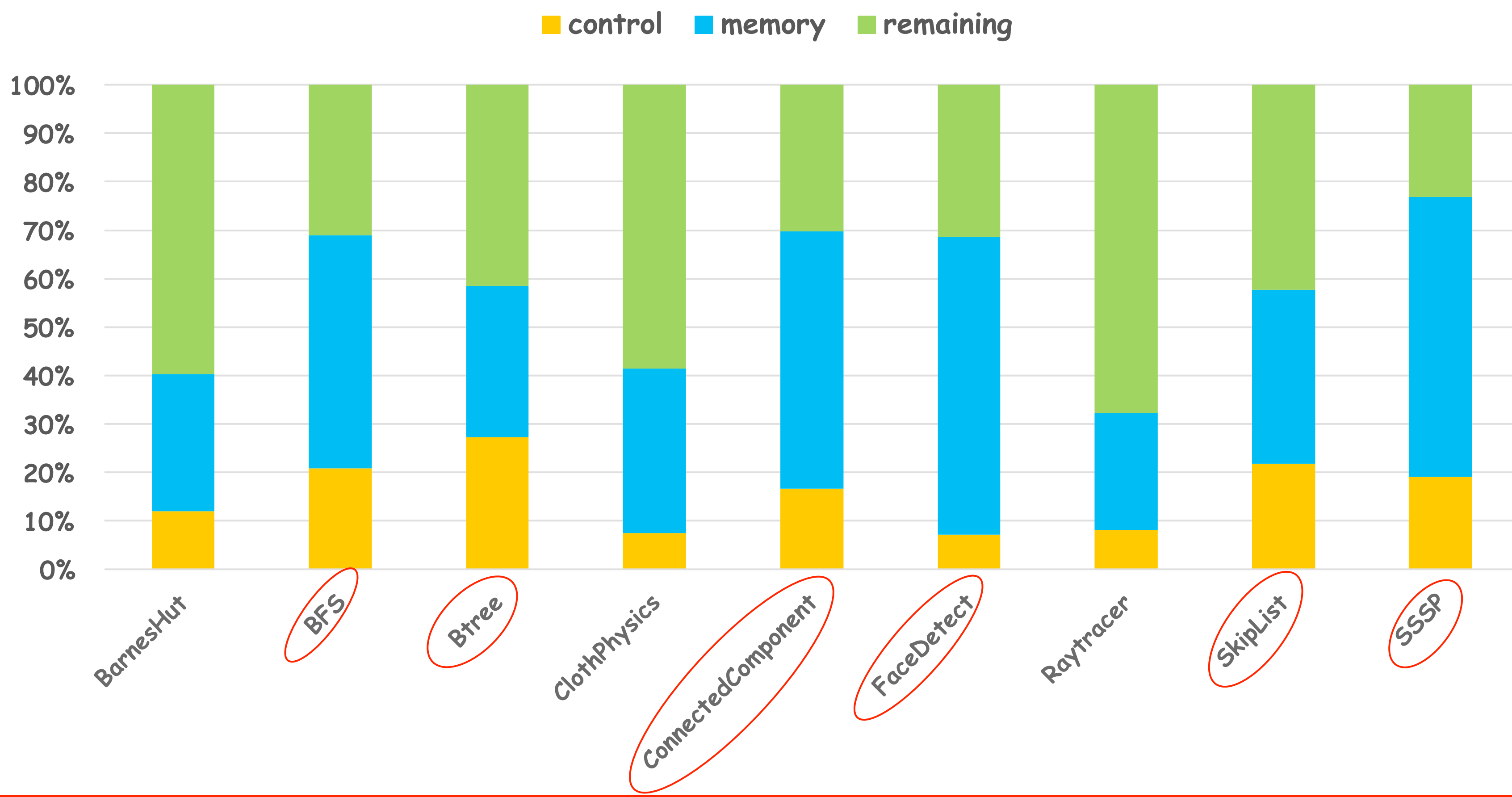
- **Comparison with multi-core CPU:**
  1. **GPU-SPEEDUP: speedup using GPU execution**
  2. **GPU-ENERGY-SAVINGS: energy savings using GPU execution**

Workloads

Benchmarks	Origin	Input	LoC	Device LoC	Data Structure	Parallel Construct
BarnesHut	In-house	1M bodies	828	105	Tree	Parallel_for
BFS	Galois	|V|=6.2M |E|=15M	866	19	Graph	Parallel_for
Btree	Rodinia	Command.txt	3111	84	Tree	Parallel_for
ClothPhysics	Intel	|V|=50K |E|=200K	9234	411	Graph	Parallel_reduce
ConnComp	Galois	|V|=6.2M |E|=15M	473	36	Graph	Parallel_for
FaceDetect	OpenCV	3000x2171	3691	378	Cascade	Parallel_for
Raytracer*	In-house	sphere=256, material=3, light=5	843	134	Graph	Parallel_for
Skip_List	In-house	50M keys	467	21	Linked-list	Parallel_for
SSSP	Galois	|V|=6.2M |E|=15M	1196	19	graph	Parallel_for

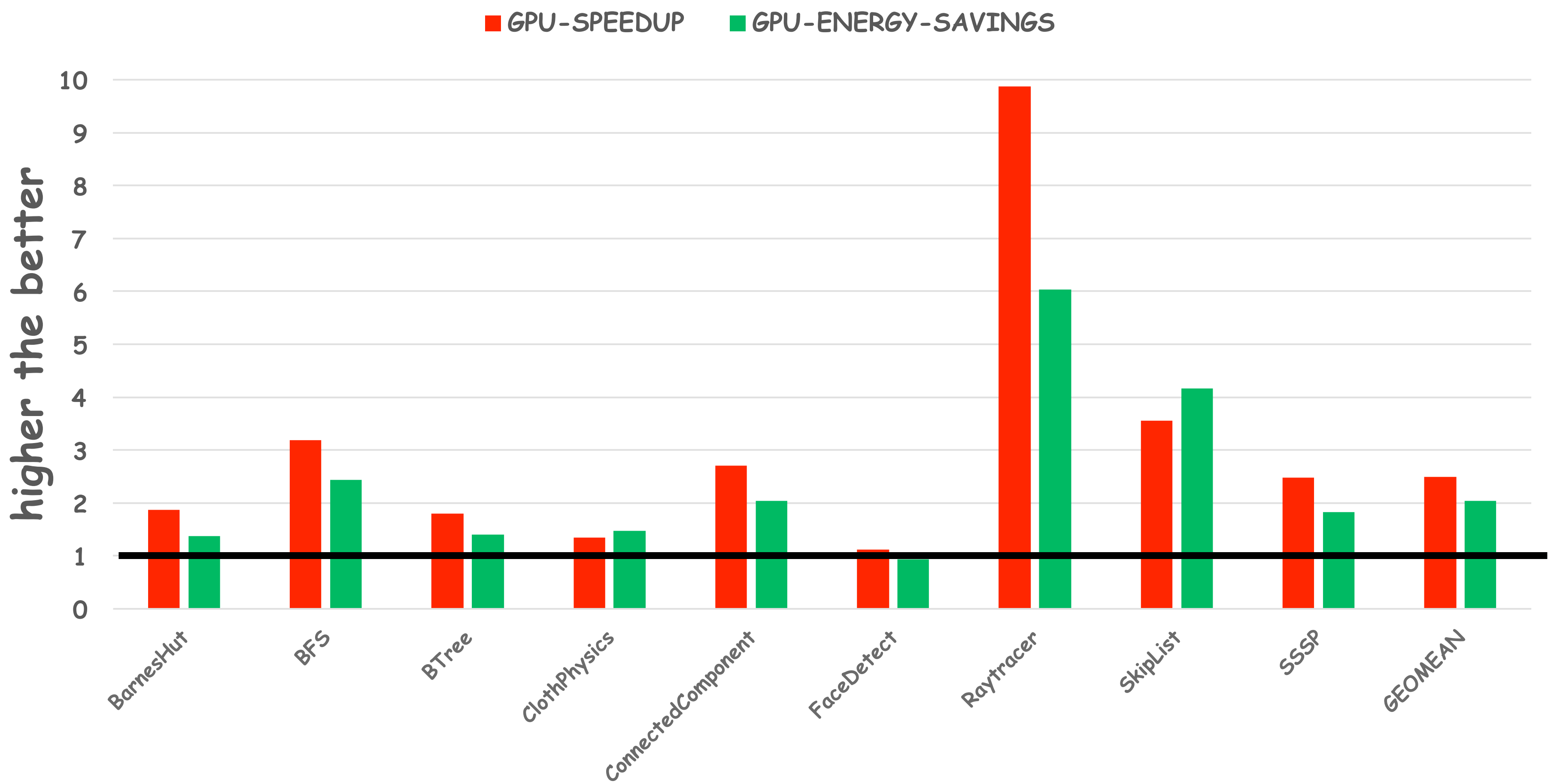
*uses virtual function

Dynamic estimates of irregularity



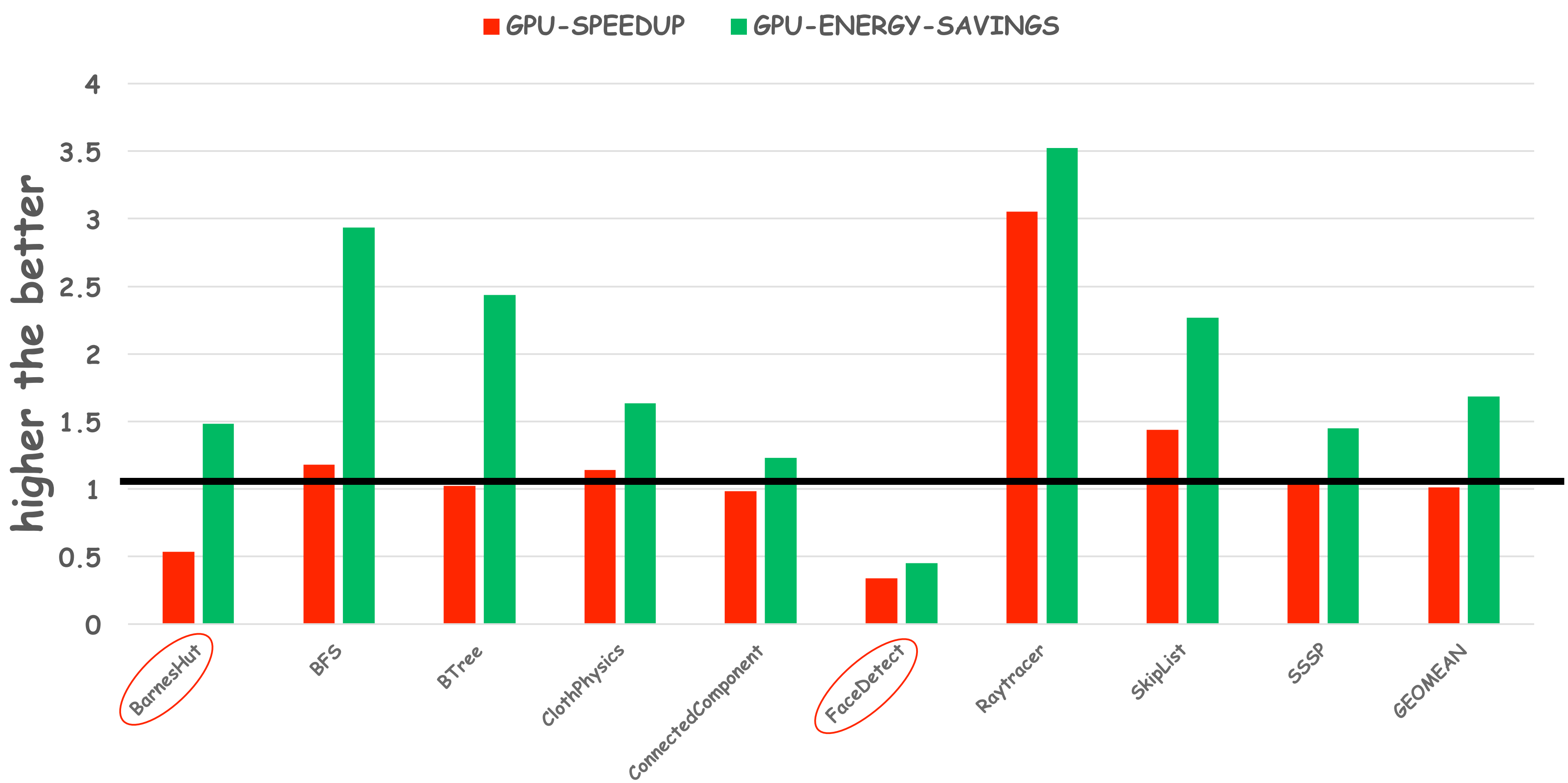
- BFS, Btree, ConnComp, FaceDetect, SkipList & SSSP exhibit a lot of irregularities (>50%)
- FaceDetect exhibits maximum percentage of memory irregularities

Ultrabook: Speedup & Energy savings compared to multicore CPU



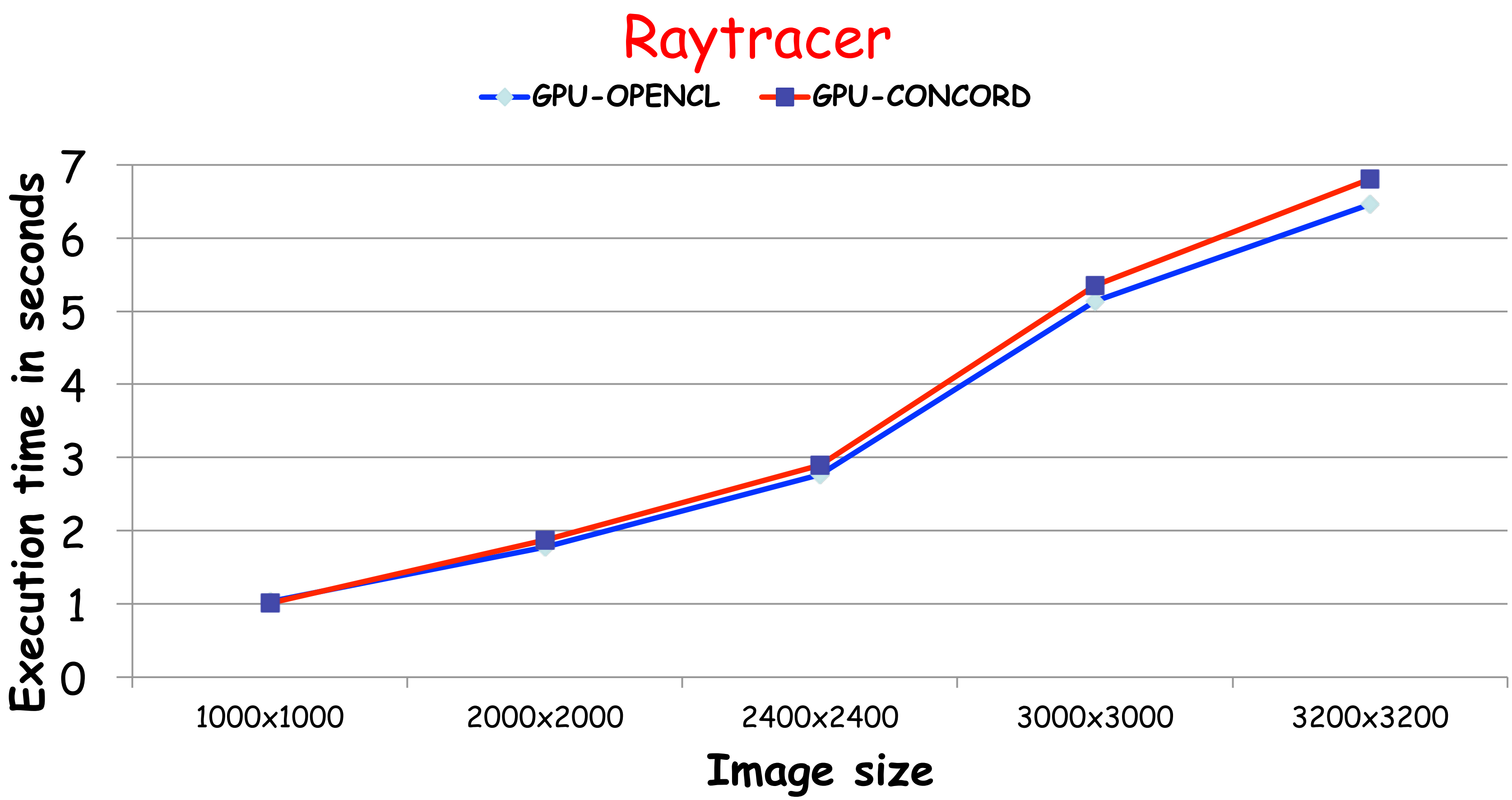
Average speedup of 2.5x and energy savings of 2x vs. multicore CPU

Desktop: Speedup & Energy savings compared to multicore CPU



Average speedup of 1.01x and energy savings of 1.7x vs. multicore CPU

Overhead of SW-based SVM implementation



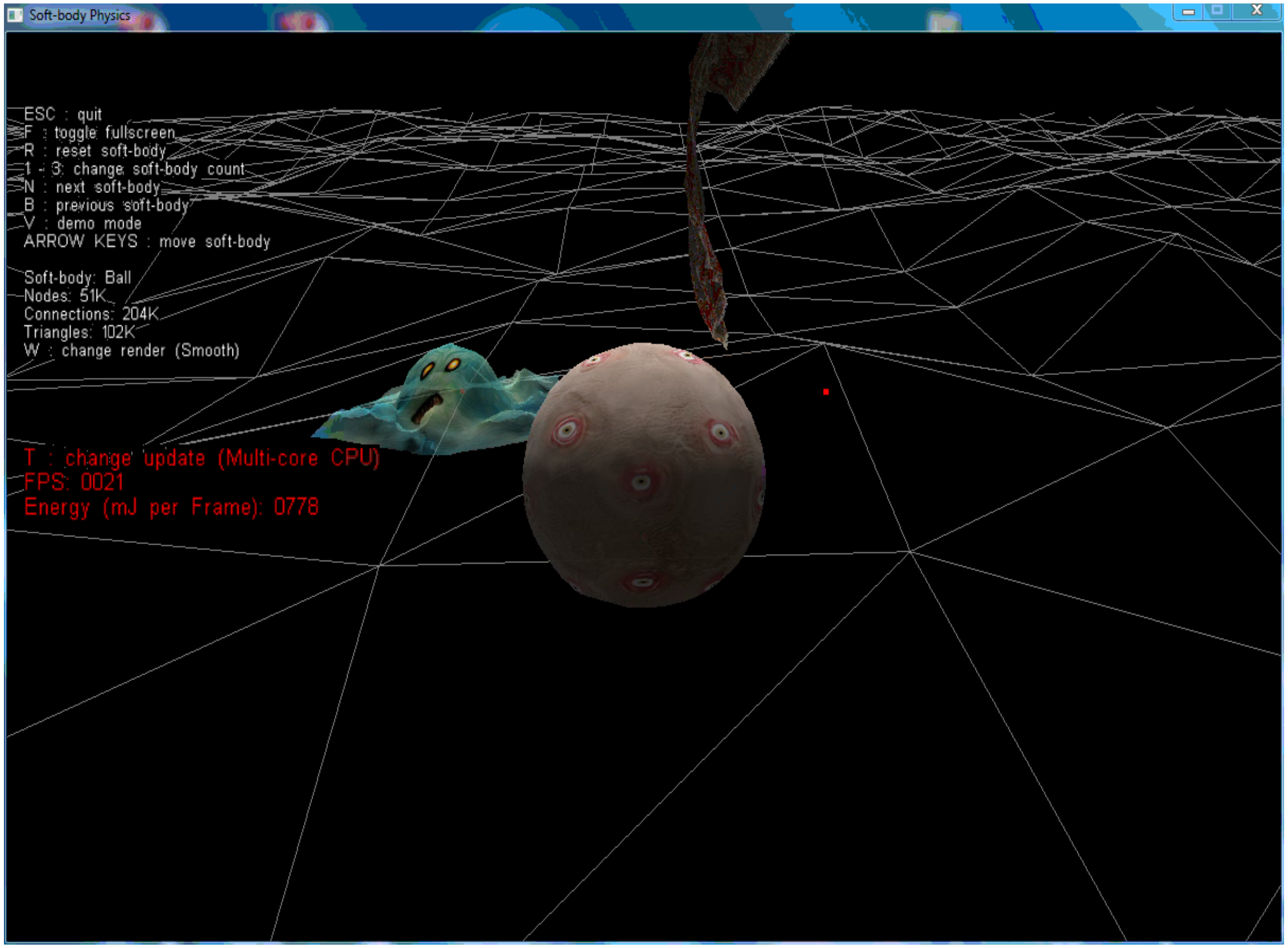
SW-based SVM overhead is negligible for smaller images and is ~6% for the largest image

Conclusions & Future work

- **Runs out-of-the-box C++ applications on GPU**
- **Demonstrates that SVM is a key enabler in programmer productivity of heterogeneous systems**
- **Implements SVM in software with low-overhead**
- **Implements virtual functions and parallel reductions on GPU**
- **Saves energy of 2.04x on Ultrabook and 1.7x on Desktop compared to multi-core CPU for irregular applications**

- **Future work:**
  - **Support advanced features on GPU: exceptions, memory allocation, locks, etc.**
  - **Support combined CPU+GPU heterogeneous execution**

Cloth Physics demo using Concord:



Questions?

Please try it out:
https://github.com/IntelLabs/iHRC/