Obsidian: GPU Kernel Programming in Haskell

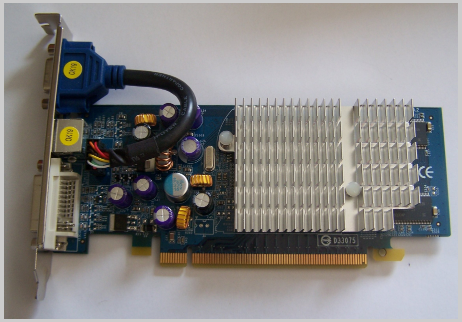
Licentiate Seminar

Discussion leader:
Prof. Andy Gill
University of Kansas

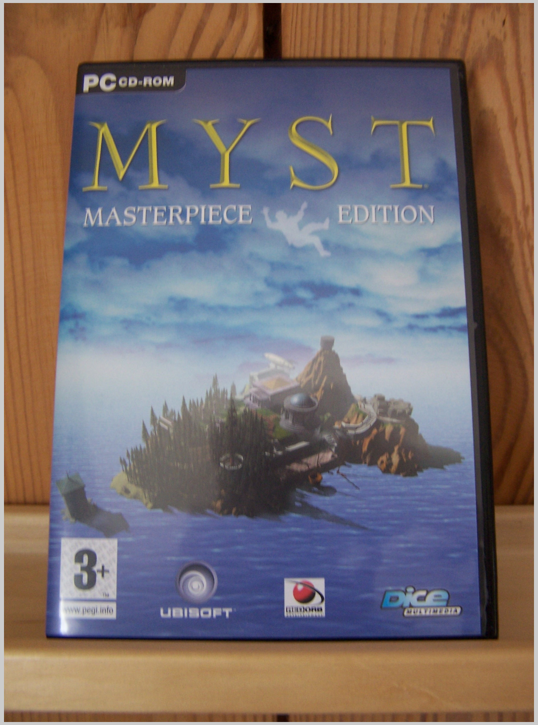
Presenter:
Joel Svensson
Chalmers University of Technology

Supervisors:
Mary Sheeran and **Koen Claessen**

GPUs



GPUs


PC CD-ROM
MYST
MASTERPIECE EDITION
3+
www.pegi.info
UBISOFT
Dice


Ultima Online
7th ANNIVERSARY EDITION
BONUS!
Includes the classic
ULTIMA IX: ASCENSION
Also includes rare in-game items!
See back of box for details.
T-M
PC CD-ROM SOFTWARE
EA GAMES
ORIGIN


PC DVD
DRAGON AGE
ORIGINS
18
www.pegi.info
BIOWARE
EA

GPUs

General Purpose Computations on GPUs (the GPGPU field)

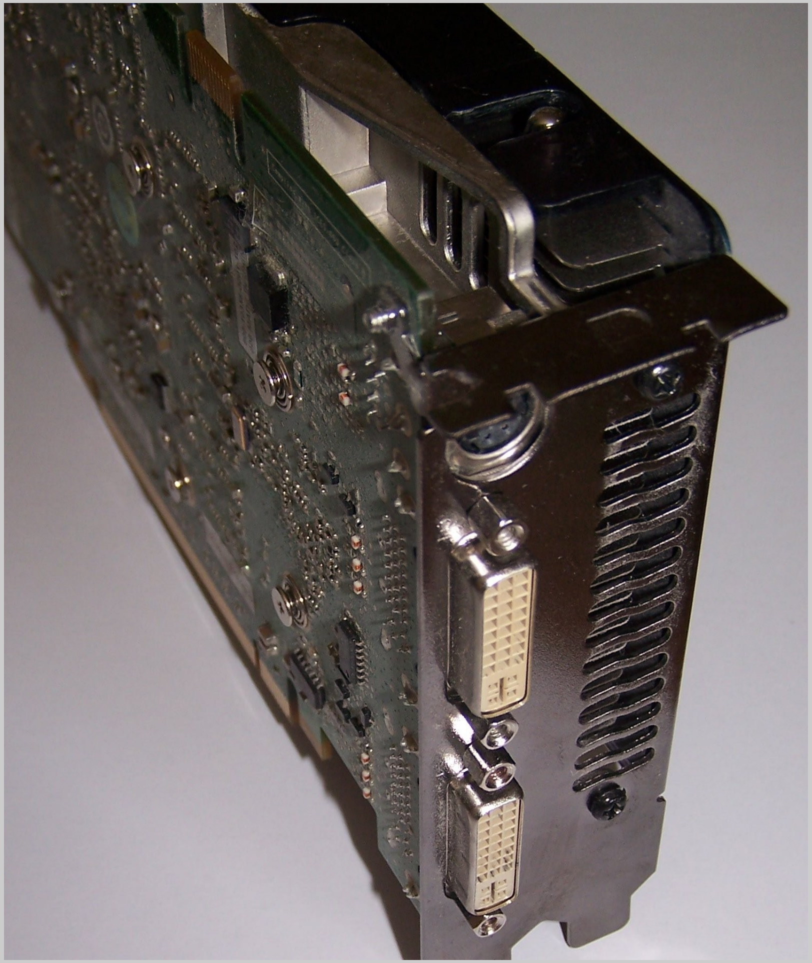
www.nvidia.com/cuda

GPGPU

- Use graphics processors for things not directly graphics related.
- Evolving area.
  - Used to be hard: “exploit” the graphics API in clever ways to make the GPU compute something
  - Greatly improved by high-level languages such as NVIDIA CUDA
- GPUs are still hard to program

NVIDIA CUDA

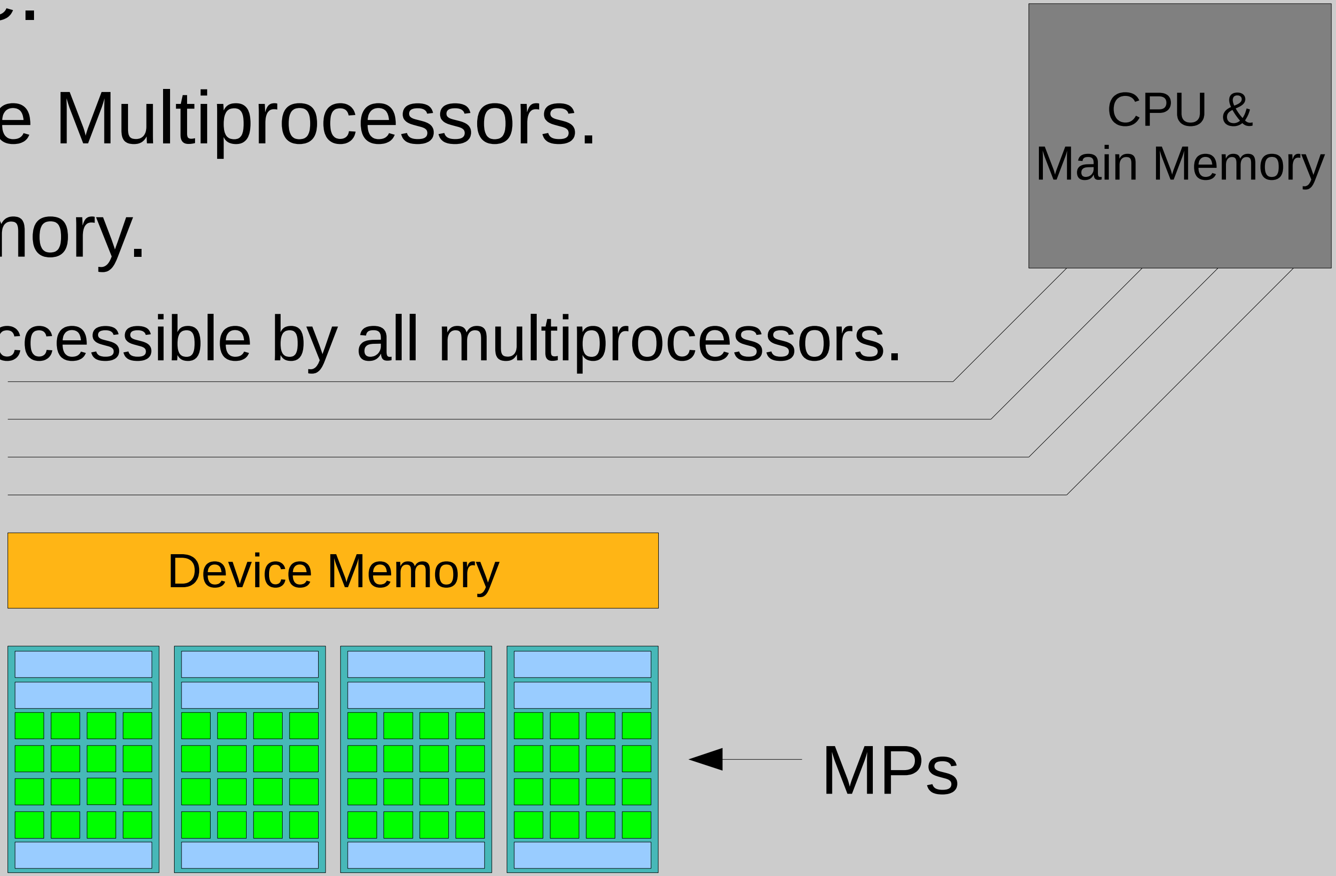
- Compute Unified Device Architecture
  - Architecture and programming model of modern NVIDIA GPUs.



GFX-Card with 8800 series GPU

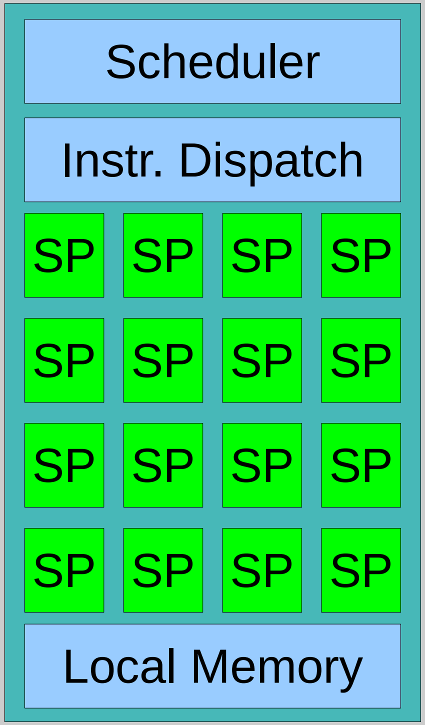
CUDA Architecture

- A CUDA GPU is based on a scalable architechture.
  - One or more Multiprocessors.
  - Device memory.
    - Memory accessible by all multiprocessors.



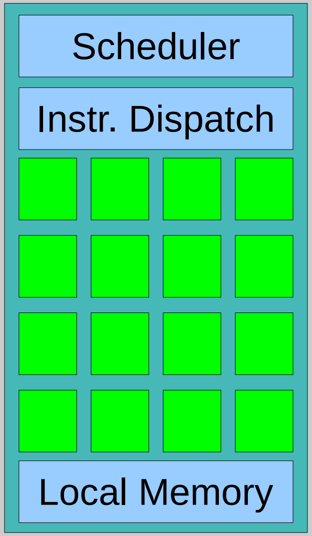
Close up on a Multiprocessor

- One MP corresponds to what people often call a “core”.
  - Has a number of processing units (SP).
    - SIMD style.
    - 8, 32 SPs (Now called “CUDA cores”)
  - Local memory accessible by the SPs.
    - Kilobytes
  - Multithreading, handled by scheduler.
    - Hundreds of threads per MP

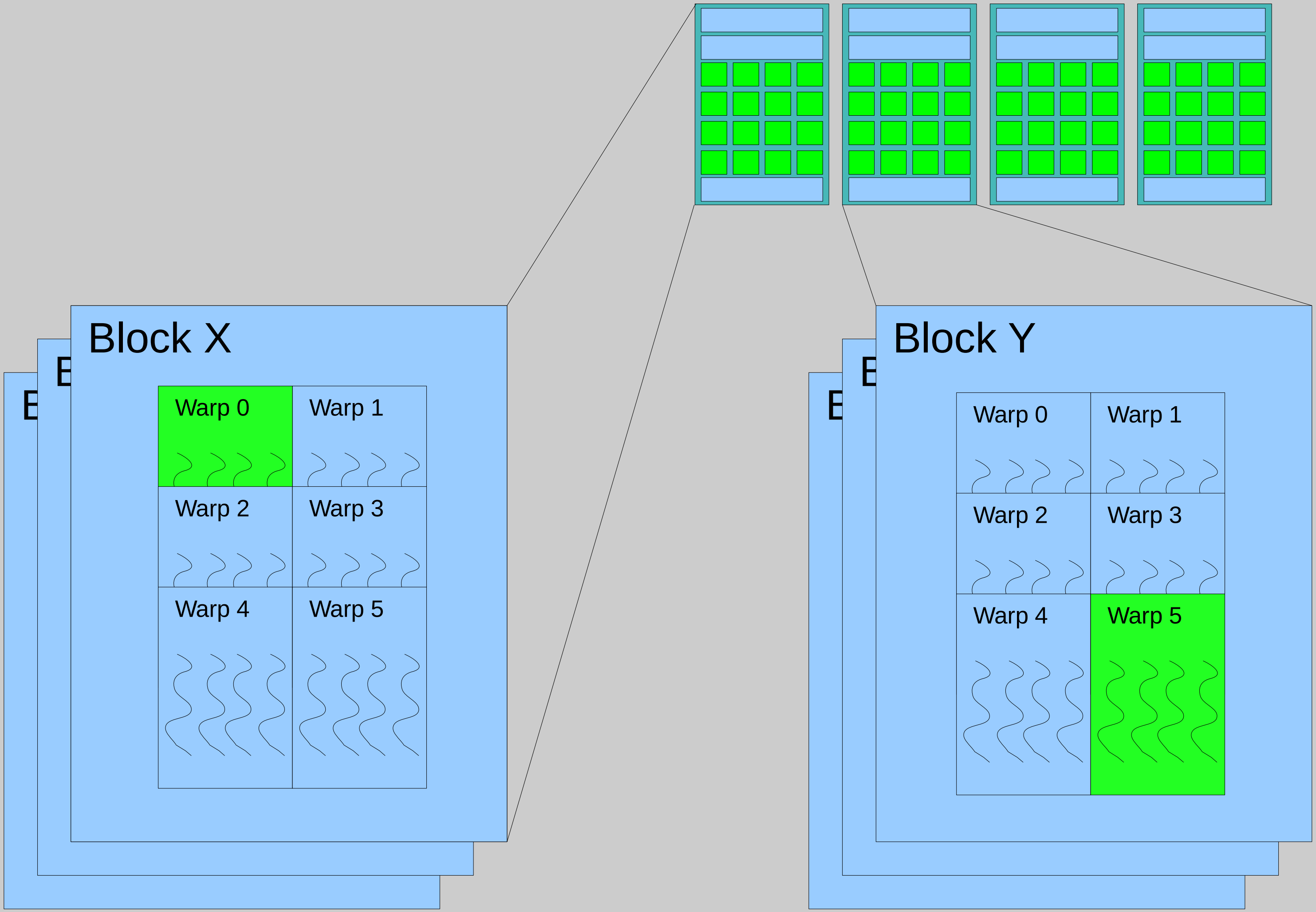


CUDA Programming Model

- Fits the scalable nature of the architecture.
- Programmer writes a “Kernel”
    - SPMD (Single Program Multiple Data) style of programming
    - Is executed on the GPU by a hierarchy of threads
        - – Threads
            - – Warps
        - – Blocks
        - – Grid



Blocks of threads



CUDA Example

CUDA Example: Dot Product

Sequential C code

```
float dotProduct(float *x, float *y, unsigned int n) {
  float r = 0.0f;
  for (int i = 0; i < n; ++i) {
    r += x[i] * y[i];
  }
  return r;
}
```

- Not what you want to do on a GPU

CUDA dotProduct

- Split computation into a multiplication phase and a summing phase.
  - Both end up being parallelizable.

CUDA dotProduct:
elementwise multiplication

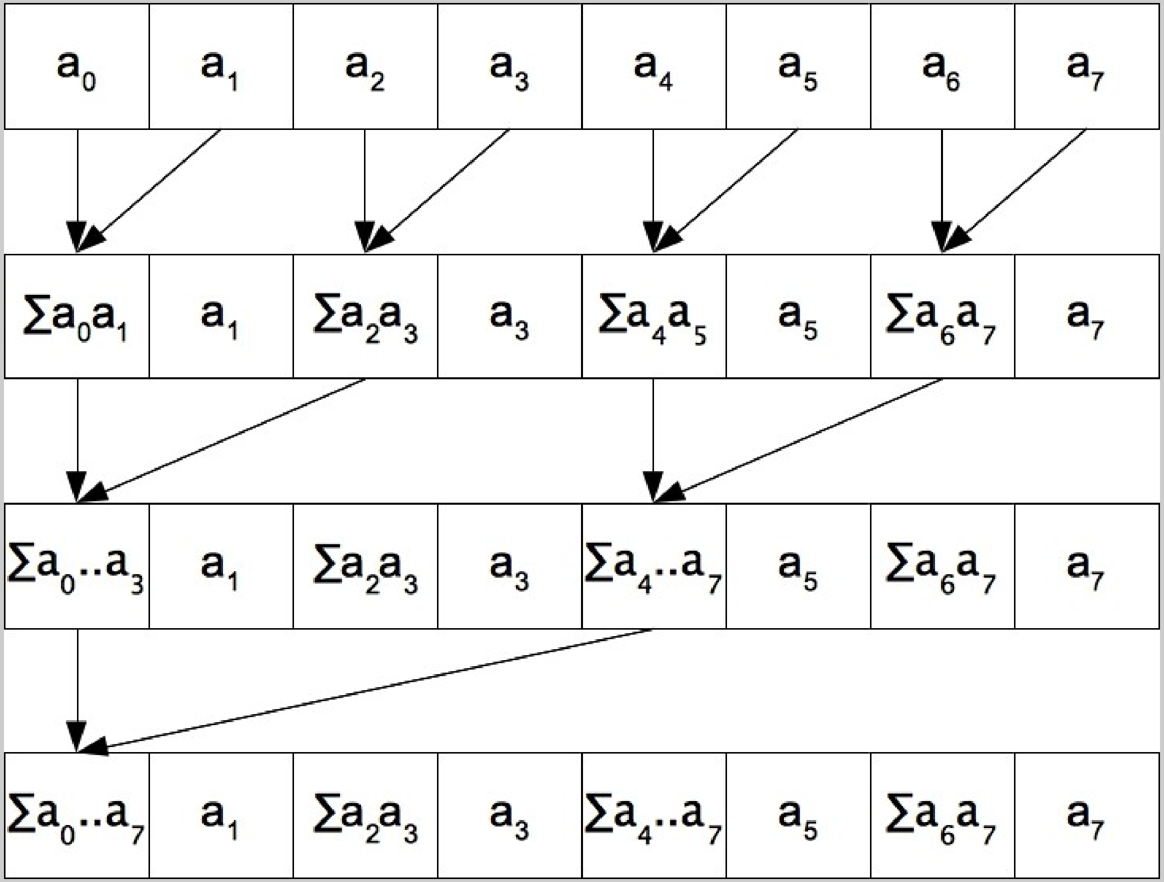
CUDA Code

```
__global__ void multKernel(float *result, float *x, *float *y){
  unsigned int gtid = blockIdx.x * blockDim.x + threadIdx.x;
  result[gtid] = x[gtid] * y[gtid];
}
```

- threadIdx: identifies a thread within a block (a vector of 3 integers)
- blockIdx: identifies a block within a grid (a vector of 2 integers)
- blockDim: specifies the extents of the blocks (a vector of 3 integers)
- __global__: specifies that this function is a CUDA kernel.

CUDA dotProduct:
summation

- Sum up the products.



CUDA dotProduct:
summation

CUDA Code

```
__global__ void sumKernel(float *result, float *x){
  unsigned int tid = threadIdx.x;

  extern __shared__ float sm[];

  sm[tid] = x[blockIdx.x * blockDim + tid];

  for (int i = 1; i < blockDim.x; i *=2) {
    __syncthreads();
    if (tid % (2*i) == 0) {
      sm[tid] += sm[tid + i];
    }
  }
  if (tid == 0) {
    result[blockIdx.x] = sm[0];
  }
}
```

- Sums up an array “that fits in a block”
- Uses shared memory
- Uses `__syncthreads()`

CUDA dotProduct

- We have:
  - A CUDA kernel that can multiply two arrays (of “any” size) element-wise.
  - A CUDA kernel that can sum up arrays
    - 32, 64,128,256, … 1024 elements for example.

CUDA dotProduct

- Launching Kernels on the GPU

CUDA Host Code

```
multKernel<<<128,512,0>>>(device_x,device_x,device_y);
sumKernel<<<128,512,512*sizeof(float)>>>(result,device_x);
sumKernel<<<1,128,128*sizeof(float)>>>(result,result);
```

- Computes the dotProduct of two (128 * 512)-element arrays.
- device_x,device_y and result arrays in “device memory”

CUDA dotProduct:
potential optimizations

- Create a fused “mult-sum” kernel

```
multSumKernel<<<128,512,0>>>(result,device_x,device_y);
sumKernel<<<1,128,128*sizeof(float)>>>(result,result);
```

- Compute more “results” per thread
  - Use fewer threads in total.
  - Better utilize memory bandwidth.
- Unroll loops, specialize kernel to a particular block-size.
  - Many few-threaded blocks, few many-threaded blocks?
- Changes like these means:
  - Rethink indexing computations.
  - Much rewriting of your kernels.

CUDA

- CUDA is a huge improvement.
- CUDA C is not C.
- Kernels are not easily composed.
- “tweaking” kernels is cumbersome.

Obsidian

Obsidian

- A language for GPU kernel implementation.
  - Embedded in Haskell.

- Goals
  - Compose kernels easily
  - Raise the level of abstraction while maintaining control.
    - Use combinators (higher order functions).
    - Building blocks view on kernel implementation.
    - Think in “data-flow” and “connection-patterns” instead of indexing
  - Generate CUDA code

Obsidian: Small Example

- Increment every element in an array

```
incrAll :: Num a => Arr a :-> Arr a
incrAll = pure$ fmap (+1)
```

- Can be executed on the GPU

```
*Main> execute incrAll [0..9 :: IntE]
[1,2,3,4,5,6,7,8,9,10]
```

Obsidian: Small Example

- Or look at the generated CUDA.

```
*Main> execute incrAll [0..9 :: IntE]
[1,2,3,4,5,6,7,8,9,10]
```

```
genKernel "incrKern" incrAll (mkArr undefined 10 :: Arr IntE)
```

Generated CUDA

```
__global__ void incrKern(word* input0,word* result0){
  unsigned int tid = (unsigned int)threadIdx.x;
  ix_int(result0,(tid + (10 * blockIdx.x))) =
   (ix_int(input0,(tid + (10 * blockIdx.x))) + 1);
}
```

Obsidian: Small Example

The details

```
incrAll :: Num a => Arr a :-> Arr a
incrAll = pure$ fmap (+1)
```

Kernel

fmap (+1) :: Arr a -> Arr a

pure :: (a -> b) -> a :-> b

Obsidian: Small Example
The details

- Arrays (Arr a)

```
data Arr a = Arr (IndexE -> a) Int
```

  - Describes how to compute an element given an index.

```
rev :: Arr a -> Arr a
rev arr  = mkArr ixf n
    where
        ixf ix = arr ! (fromIntegral (n-1) - ix)
        n = len arr
```

```
 fmap f arr = mkArr (\ix -> f (arr ! ix)) (len arr)
```

Obsidian: Small Example

The details

AST

```
*Main> execute incrAll [0..9 :: IntE]
[1,2,3,4,5,6,7,8,9,10]
```

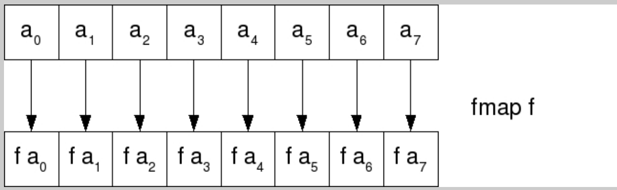
AST

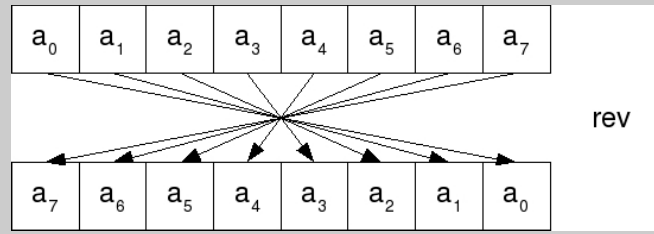
```
genKernel "incrKern" incrAll (mkArr undefined 10 :: Arr IntE)
```

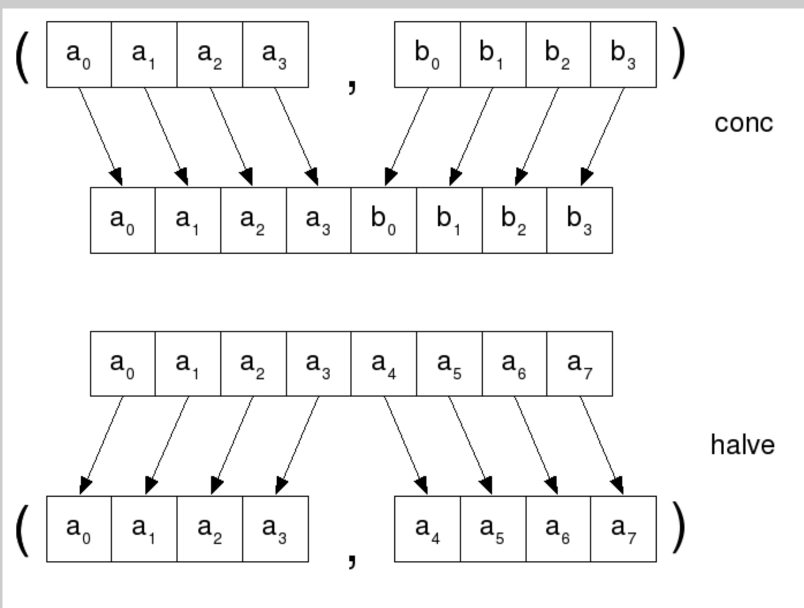
?

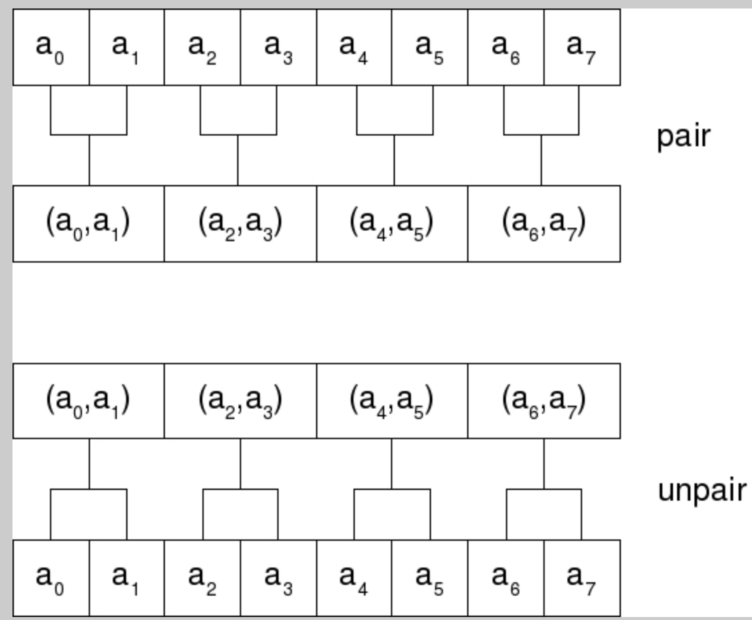
```
data DExp
  = LitInt Int
   | LitUInt Word32
   | LitBool Bool
   | LitFloat Float
   | Op2 Op2 DExp DExp
   | Op1 Op1 DExp
   | If DExp DExp Dexp
     ...

type Exp a = E DExp
type IntE  = Exp Int
```

Building Blocks

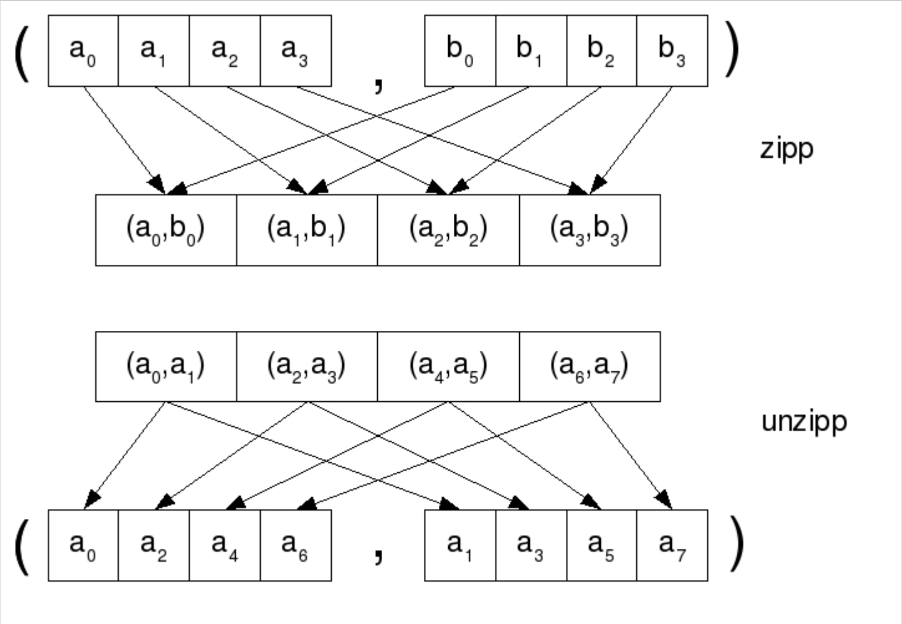


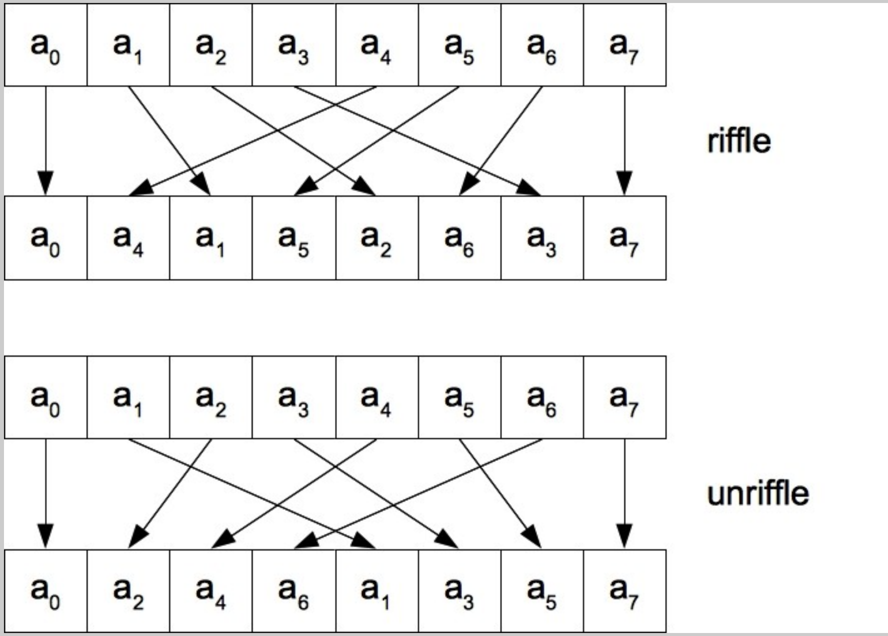






Building Blocks





Obsidian:
Expanding the small example

```
incrRev0 :: Num a => Arr a :-> Arr a
incrRev0 = incrAll ->- pure rev
```

- Sequential composition of Kernels.

```
*Main> execute incrRev0 [0..9 :: IntE]
[10,9,8,7,6,5,4,3,2,1]
```

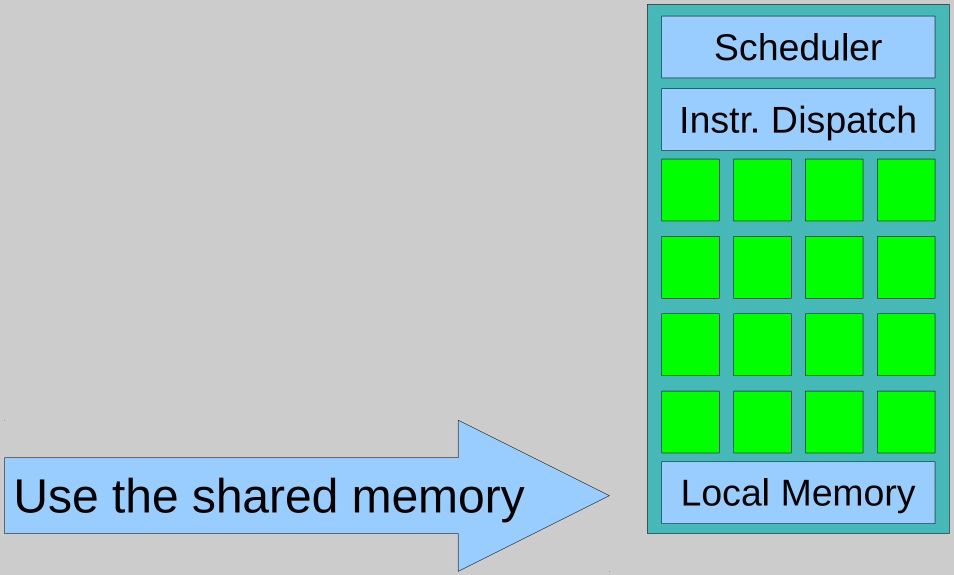
Obsidian:
Expanding the small example

```
incrRev1 :: Num a => Arr a :-> Arr a
incrRev1 = pure$ rev . fmap (+1)
```

- Could have used Haskell function composition for same result.

```
*Main> execute incrRev1 [0..9 :: IntE]
[10,9,8,7,6,5,4,3,2,1]
```

Obsidian:
Expanding the small example




```
incrRev2 :: (Flatten a, Num a) => Arr a :-> Arr a
incrRev2 = incrAll ->- sync ->- pure rev
```

- Store intermediate result in shared memory.

```
*Main> execute incrRev2 [0..9 :: IntE]
[10,9,8,7,6,5,4,3,2,1]
```

The generated code

```
__global__ void incrRev1(word* input0,word* result0){
  unsigned int tid = (unsigned int)threadIdx.x;
  ix_int(result0,(tid + (10 * blockIdx.x))) =
    (ix_int(input0,((9 - tid) + (10 * blockIdx.x))) + 1);
}
```

```
__global__ void incrRev2(word* input0,word* result0){
  unsigned int tid = (unsigned int)threadIdx.x;
  extern __shared__ unsigned int s_data[];
  word __attribute__((unused)) *sm1 = &s_data[0];
  word __attribute__((unused)) *sm2 = &s_data[10];
  ix_int(sm1,tid) =
    (ix_int(input0,(tid + (10 * blockIdx.x))) + 1);
  __syncthreads();
  ix_int(result0,(tid + (10 * blockIdx.x))) =
    ix_int(sm1,(9 - tid));
}
```

Seen so far

- Create kernels.

  `pure`

- Sequential composition of kernels.

  `->-`

- Store intermediate results in shared memory or “fuse” computations.

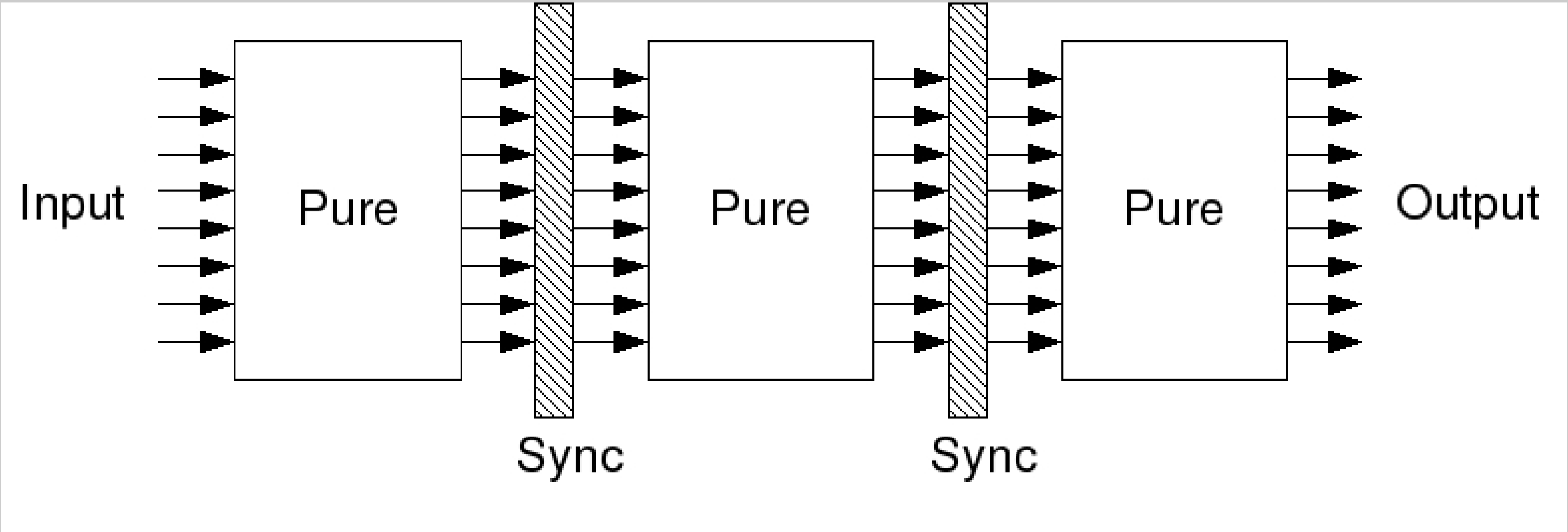
  `sync`

- Combinators and permutations.

  `fmap` and `rev`

- Length of array specifies degree of parallelism

Obsidian Kernels




```
data a :-> b where
    Pure  :: (a -> b) -> (a :-> b)
    Sync  :: (a -> Arr FData) -> (Arr FData :-> b) -> (a :-> b)
```

Obsidian: dotProduct

- Same approach as in the CUDA example
  - A multKernel and one sumKernel

```
multKern :: (Arr FloatE, Arr FloatE) :-> Arr FloatE
multKern = pure$ zipWith (*)
```

Obsidian: dotProduct

- Implement a similar binary tree shaped summation as in the CUDA example.

```
reduce :: Flatten a => Int -> (a -> a -> a) -> Arr a :-> Arr a
reduce 0 f = pure id
reduce n f = pure op ->- sync ->- reduce (n-1) f
    where
      op = fmap (uncurry f) . pair
```

- Sync is used to obtain parallelism.

Obsidian: dotProduct

```
dotProduct :: Int -> (Arr FloatE, Arr FloatE) :-> Arr FloatE
dotProduct n = multKern ->- sync ->- reduce n (+)
```

Obsidian: dotProduct
Generated Code

```
__global__ void dotProduct(word* input0,word* input1,word* result0){
  unsigned int tid = (unsigned int)threadIdx.x;
  extern __shared__ unsigned int s_data[];
  word __attribute__((unused)) *sm1 = &s_data[0];
  word __attribute__((unused)) *sm2 = &s_data[8];
  ix_float(sm1,tid) = (ix_float(input0,(tid + (8 * blockIdx.x))) *
                       ix_float(input1,(tid + (8 * blockIdx.x))));
  __syncthreads();
  if (tid < 4){
    ix_float(sm2,tid) = (ix_float(sm1,(tid << 1)) +
                         ix_float(sm1,((tid << 1) + 1)));
  }
  __syncthreads();
  if (tid < 2){
    ix_float(sm1,tid) = (ix_float(sm2,(tid << 1)) +
                         ix_float(sm2,((tid << 1) + 1)));
  }
  __syncthreads();
  if (tid < 1){
    ix_float(sm2,tid) = (ix_float(sm1,(tid << 1)) +
                         ix_float(sm1,((tid << 1) + 1)));
  }
  __syncthreads();
  if (tid < 1){
    ix_float(result0,(tid + blockIdx.x)) = ix_float(sm2,tid);
  }
}
```

Obsidian

CUDA dotProduct:
potential optimizations

- Create a fused “mult-sum” kernel

Easy

```
multSumKernel<<<128,512,0>>>(result,device_x,device_y);
sumKernel<<<1,128,128*sizeof(float)>>>(result,result);
```

- Compute more “results” per thread

Not as easy as we like

  - Use fewer threads in total.
  - Better utilize memory bandwidth.
- Unroll loops, specialize kernel to a particular block-size

Ok

  - Many few-threaded blocks, few many-threaded blocks?

The reversed is hard

- Changes like these means:
  - Rethink indexing computations.
  - Much rewriting of your kernels.

Case Studies

Case Studies

- Reduction
- Dot product
- Mergers
- Sorters
- Parallel prefix

Case Studies:
dotProduct

```
dotProduct0 :: Int -> (Arr FloatE, Arr FloatE) :-> Arr FloatE
dotProduct0 n = multKern ->- sync ->- reduce n (+)
```

```
dotProduct1 :: Int -> (Arr FloatE, Arr FloatE) :-> Arr FloatE
dotProduct1 n = multKern ->- reduce n (+)
```

Kernel	Threads per block	Elems. per block	ms per block
dotProduct0	256	2*256	0.0015
dotProduct1	128	2*256	0.0013
CUDA	256	2*256	0.0030

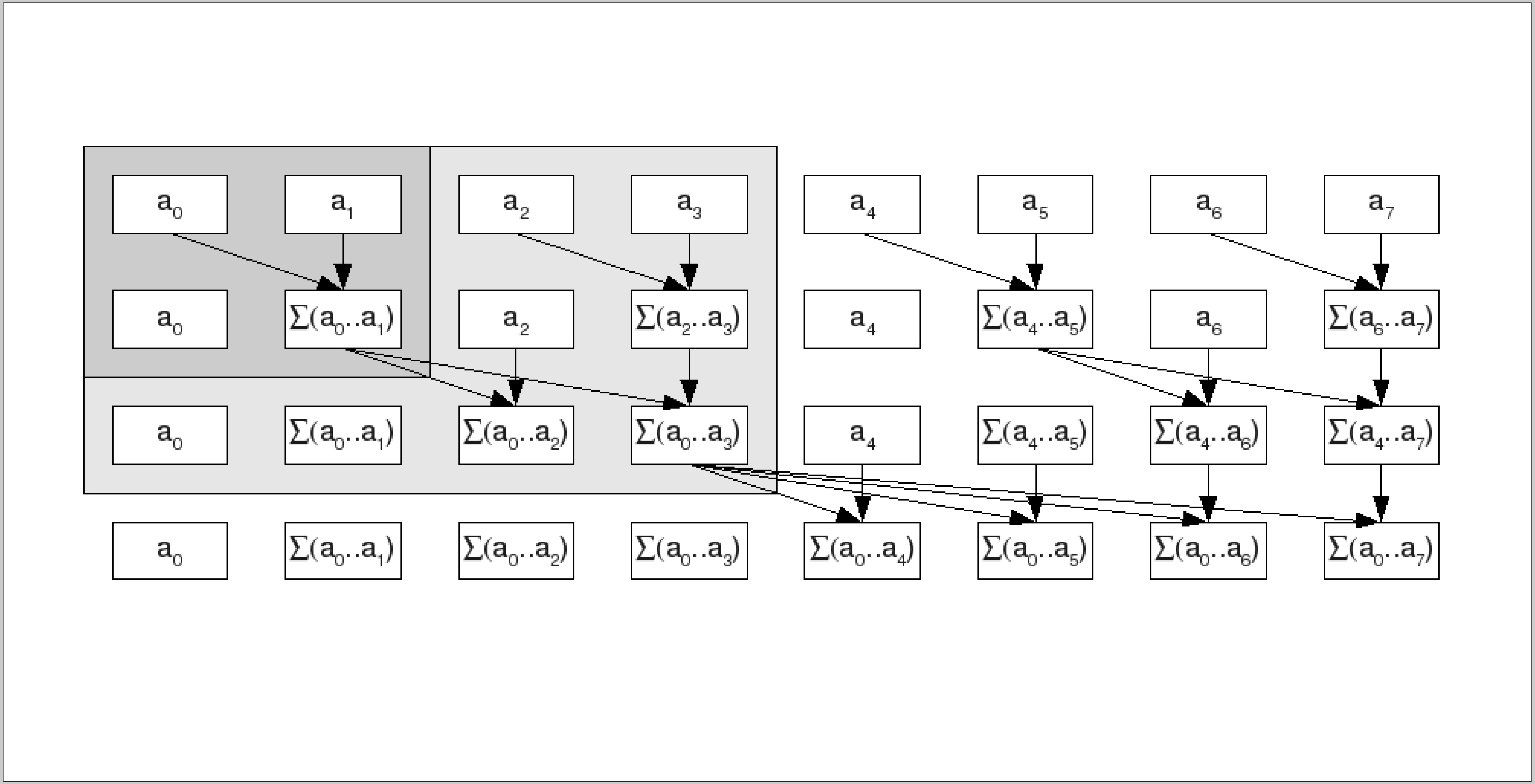
Case Studies:
Parallel prefix

- Given an associative binary operator, ⊕, and an array s, compute:

```
r[0] = s[0]
r[1] = s[0]⊕ s[1]
r[2] = s[0]⊕ s[1]⊕ s[2]
…
r[n] = s[0]⊕ … ⊕ s[n]
```

- A building block in many parallel algorithms
  - Stream compaction
  - Sorting
  - Many examples in: Prefix Sums and Their Applications - Guy E. Blelloch

Case Studies:
Parallel prefix



Case Studies:
Parallel prefix

```
sklansky :: (Flatten a, Choice a) =>
             Int -> (a -> a -> a) -> (Arr a :-> Arr a)
sklansky 0 op = pure id
sklansky n op = two (sklansky (n-1) op) ->- pure (fan op)
                   ->- sync

fan op arr = conc (a1, (fmap (op c) a2))
    where (a1,a2) = halve arr
          c       = a1 ! (fromIntegral (len a1 - 1))
```

Kernel	Threads	ms on GTX320M	ms on GTX480
Handcoded no opt.	512	4.36	0.34
Handcoded opt.	256	2.93	0.23
Obsidian Generated	512	3.84	0.32

Obsidian

- Language for implementing kernels
  - No “kernel coordination”

- Kernel composition is easy

  `->-` sequentially

  `two` special kind of parallel composition

- Kernels use shared memory for intermediate results.

Related Work

- Data.Array.Accelerate
  - Higher level language compared to Obsidian.
    - Map, Fold, ZipWith – primitives.
  - Not the same detailed control.
  - Most complete and well developed tool for Haskell based GPU programming today.

Related Work

- Nikola
  - Higher level language compared to Obsidian.
    - Similar to Accelerate in that sense.
  - Effort seems to be in developing methods for EDSL implementation.

Related Work

- Copperhead (Data-parallel python)
  - Compiles a subset of Python into CUDA for GPU execution.
  - Very fresh.

Conclusions and Future work

- Obsidian strong sides.
  - Elegant descriptions of kernels.
  - Compositional kernels.

- Kernel Coordination is needed.
  - Depending on path of GPU evolution.
- Kernel Performance can be improved.
  - Hard to compare performance to that of related work.

Extra Generated Code

```
__global__ void sklansky128(word* input0,word* result0){
  unsigned int tid = (unsigned int)threadIdx.x;
  extern __shared__ unsigned int s_data[];
  word __attribute__((unused)) *sm1 = &s_data[0];
  word __attribute__((unused)) *sm2 = &s_data[128];
  ix_int(sm1,tid) = (((tid & 0xffffff81) < 1) ?
    ix_int(input0,(tid + (128 * blockIdx.x))) :
    (ix_int(input0,((tid & 0x7e) + (128 * blockIdx.x))) +
     ix_int(input0,(tid + (128 * blockIdx.x)))));
  __syncthreads();
  ix_int(sm2,tid) = (((tid & 0xffffff83) < 2) ?
    ix_int(sm1,tid) :
    (ix_int(sm1,((tid & 0x7c) | 0x1)) + ix_int(sm1,tid)));
  __syncthreads();
  ix_int(sm1,tid) = (((tid & 0xffffff87) < 4) ?
  ix_int(sm2,tid) :
  (ix_int(sm2,((tid & 0x78) | 0x3)) + ix_int(sm2,tid)));
  __syncthreads();
  ix_int(sm2,tid) = (((tid & 0xffffff8f) < 8) ?
  ix_int(sm1,tid) :
  (ix_int(sm1,((tid & 0x70) | 0x7)) + ix_int(sm1,tid)));
  __syncthreads();
  ix_int(sm1,tid) = (((tid & 0xffffff9f) < 16) ?
  ix_int(sm2,tid) :
  (ix_int(sm2,((tid & 0x60) | 0xf)) + ix_int(sm2,tid)));
  __syncthreads();
  ix_int(sm2,tid) = (((tid & 0xffffffbf) < 32) ?
  ix_int(sm1,tid) :
  (ix_int(sm1,((tid & 0x40) | 0x1f)) + ix_int(sm1,tid)));
  __syncthreads();
  ix_int(sm1,tid) = ((tid < 64) ?
  ix_int(sm2,tid) :
  (ix_int(sm2,63) + ix_int(sm2,tid)));
  __syncthreads();
  ix_int(result0,(tid + (128 * blockIdx.x))) = ix_int(sm1,tid);
}
```