UCDAVIS

IDAV Institute for Data Analysis and Visualization

CUDPP
CUDA Data-Parallel Primitives Library

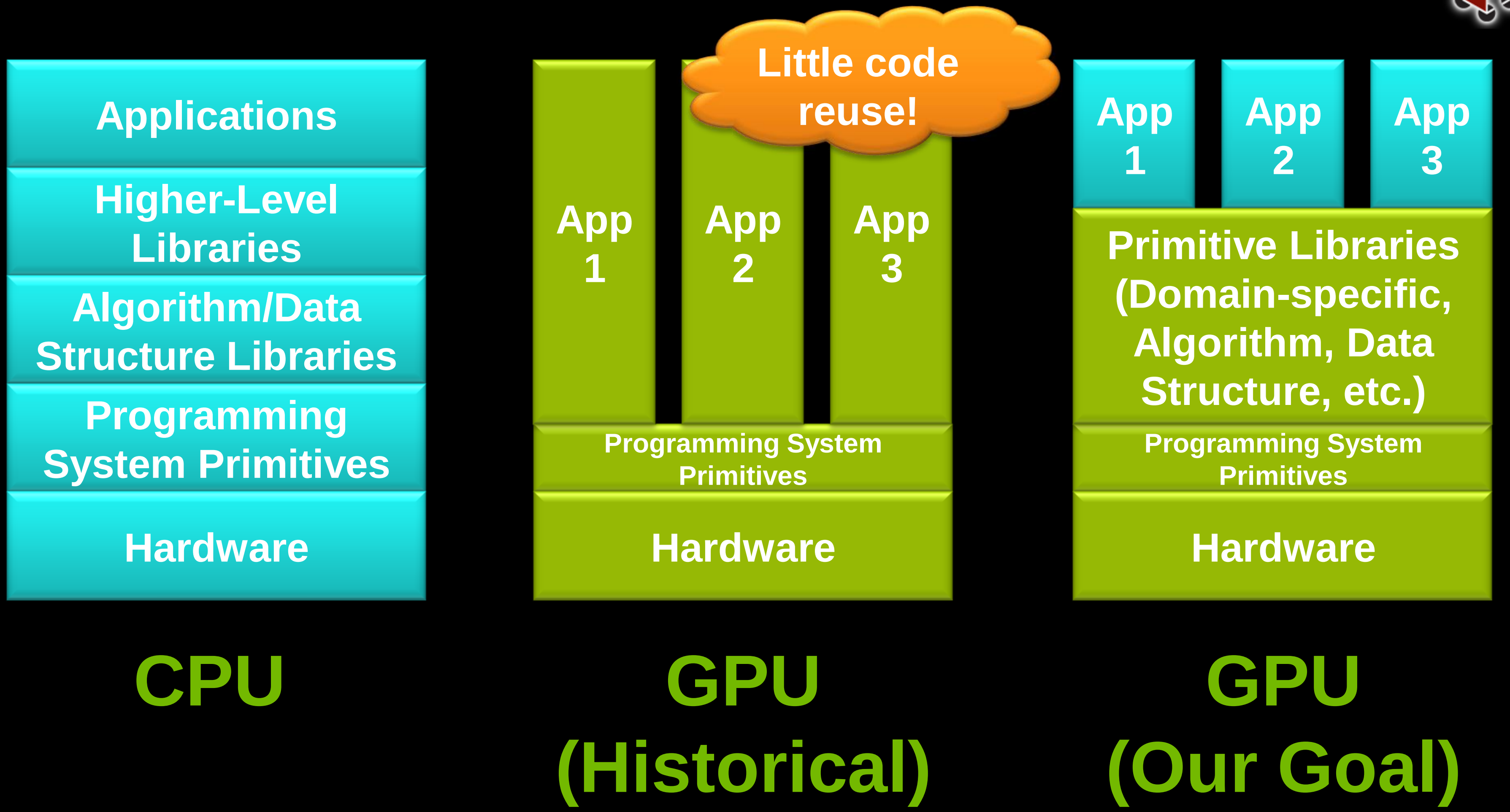
Data Parallel

- The GPU is a data-parallel processor
  - Many cores, thousands of parallel threads
  - Thousands of data elements to process
  - All data processed by the same program
    - SIMT computation model (i.e. threads may diverge)
  - Contrast with task parallelism and ILP
- Best results when you “Think Data Parallel”
  - Design algorithms for data parallelism
  - Understand parallel algorithmic complexity and efficiency
  - Use data-parallel algorithmic primitives as building blocks: CUDPP

Challenge: Libraries

- What are the…
  - …fundamental parallel algorithms?
  - …fundamental parallel data structures?
  - …methods to bring them together?
- Goal: library of fundamental parallel primitives and algorithms
  - With best-in-class performance and efficiency
  - For data-parallel (many-core) GPUs
- Result: CUDPP

Horizontal vs. Vertical Development



CUDPP

- Library of high-performance parallel primitives for GPUs
  - Written in C for CUDA
  - Runs on all CUDA-capable GPUs (100M+ shipped)
  - Support for Windows, Linux, and OS X
- Collaboration between UC Davis and NVIDIA
  - John Owens (UC Davis)
    - Shubho Sengupta, Yao Zhang, Andrew Davidson, Stanley Tzeng
  - Mark Harris (NVIDIA)
- http://code.google.com/p/cudpp

CUDPP

- Current in CUDPP:
  - (Segmented) scan, stream compact
  - Radix sort, sparse matrix-vector multiply
  - Random number generation
- In progress:
  - Parallel reduction, more sorts, graphs, trees
- Open Source under BSD License
- http://code.google.com/p/cudpp

CUDPP Design Principles

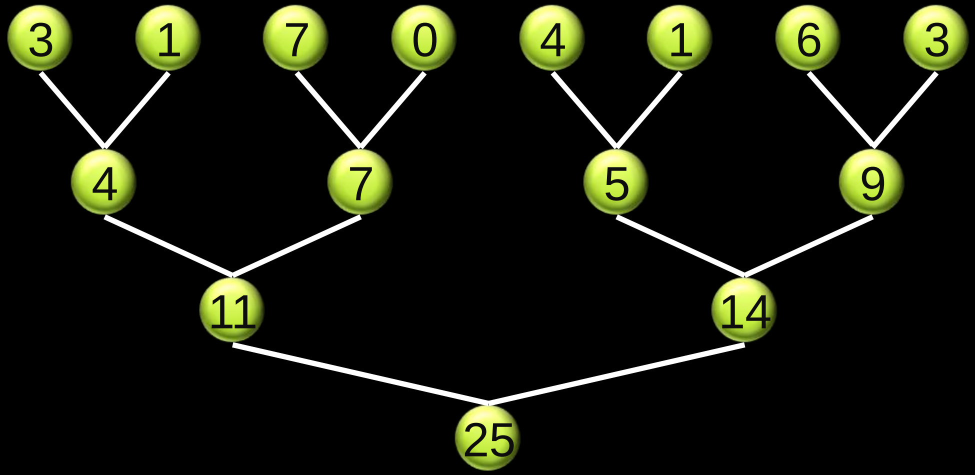
- Performance
  - Provide fundamental primitives with best-of-class performance
- CUDPP functions run on the GPU on GPU data
  - CUDPP doesn’t handle allocation or data transfers
- Modularity
  - Easily include primitives in applications
  - Library can be linked to other applications
  - Code from the multiple abstraction levels can be re-used (e.g. kernels, or cta-level __device__ functions, in addition to library-level calls)

Common Situations in Parallel Computation

- Many parallel threads need to generate a single result value
  - Reduce
- Many parallel threads that need to partition data
  - Split
- Many parallel threads and variable output per thread
  - Compact / Expand / Allocate

Parallel Reductions

- Common Data Parallel Operation
- **Reduce** vector to a single value
- Operator: +, *, min/max, AND/OR
  - Binary associative operators
- Tree-based implementation



Split Operation

- Given an array of true and false elements (and payloads)

Flag	T	F	F	T	F	F	T	F
Payload	3	1	7	0	4	1	6	3

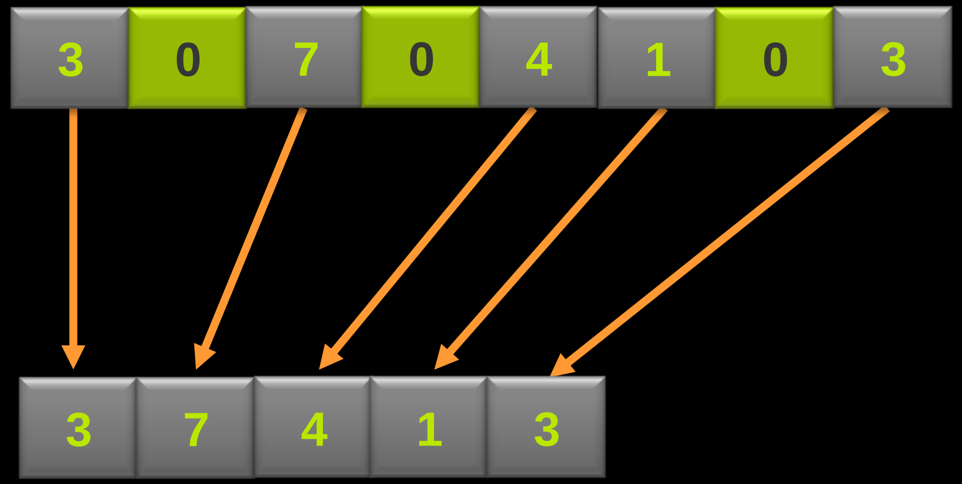
- Return an array with all true elements at the beginning

T	T	T	F	F	F	F	F
3	0	6	1	7	4	1	3

- Examples: sorting, building trees

Variable Output Per Thread: Compact

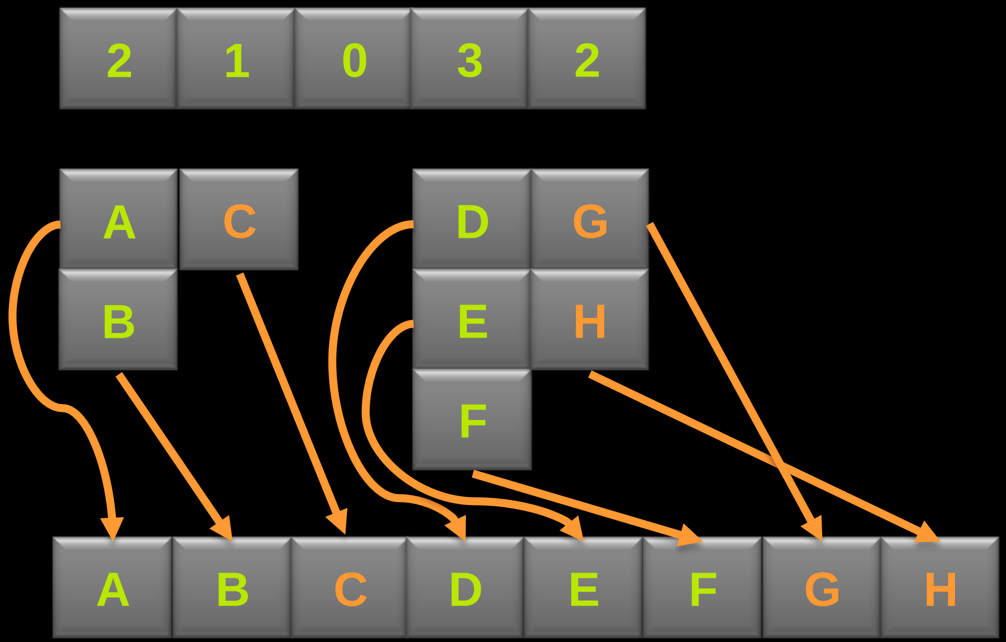
- Remove null elements



- Example: collision detection

Variable Output Per Thread: General Case

- Allocate Variable Storage Per Thread



- Examples: marching cubes, geometry generation

“Where do I write my output?”

- In all of these situations, each thread must answer that simple question

- The answer is:

  “That depends (on how much the other threads need to write)!”

- “Scan” is an efficient way to answer this question in parallel

Parallel Prefix Sum (Scan)

- Given an array $A = [a_0, a_1, \ldots, a_{n-1}]$
  and a binary associative operator $\oplus$ with identity I,

$$\text{scan}(A) = [I, a_0, (a_0 \oplus a_1), \ldots, (a_0 \oplus a_1 \oplus \ldots \oplus a_{n-2})]$$

- Example: if $\oplus$ is addition, then scan on the set

[3 1 7 0 4 1 6 3]

returns the set

[0 3 4 11 11 15 16 22]

Scan Literature

Pre-GPU

- First proposed in APL by Iverson (1962)
- Used as a data parallel primitive in the Connection Machine (1990)
  - Feature of C* and CM-Lisp
- Guy Blelloch used scan as a primitive for various parallel algorithms
  - *Blelloch, 1990, “Prefix Sums and Their Applications”*

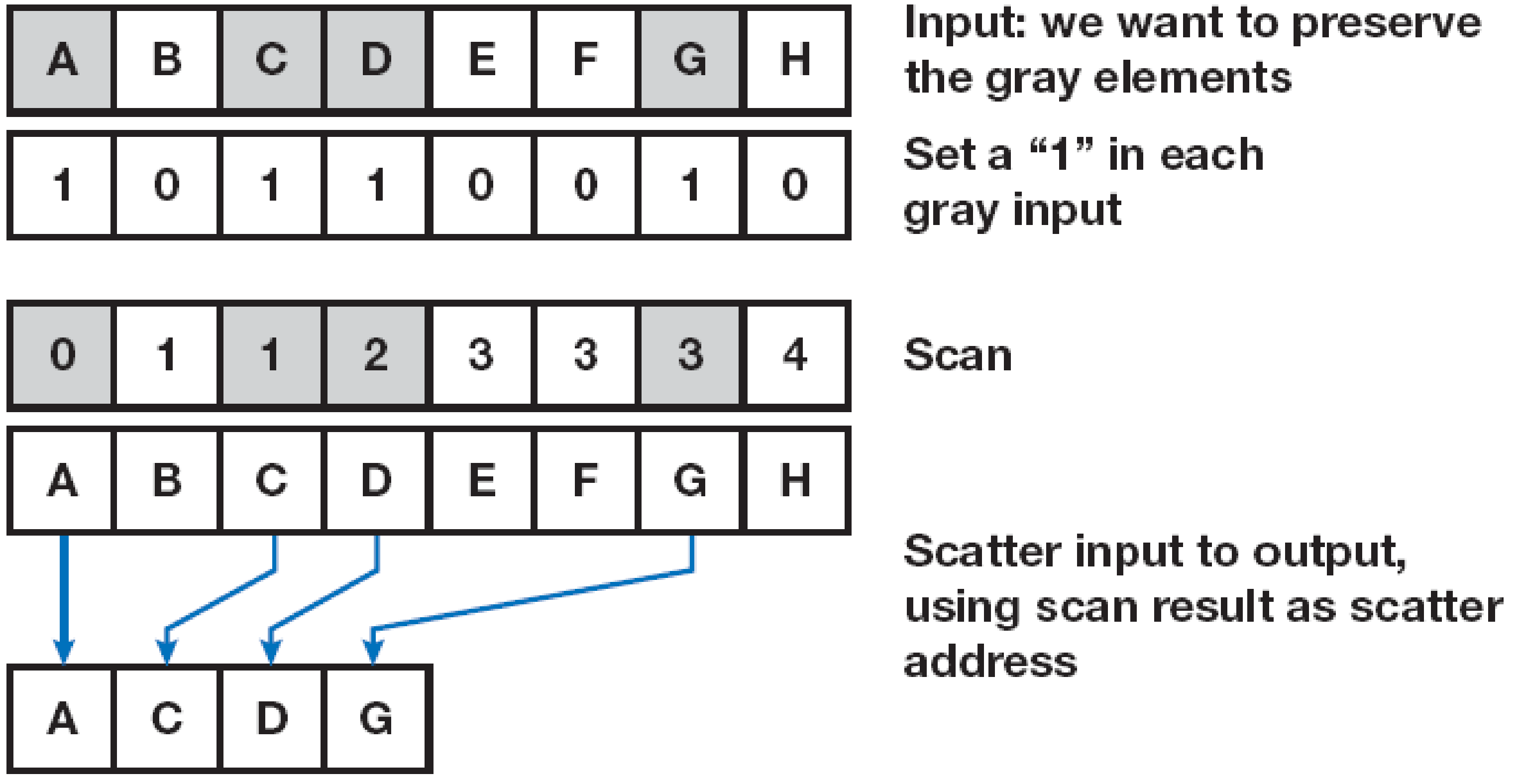
Post-GPU

- O(n log n) work GPU implementation by Daniel Horn (GPU Gems 2)
  - Applied to Summed Area Tables by Hensley et al. (EG05)
- O(n) work GPU scan by Sengupta et al. (EDGE06) and Greß et al. (EG06)
- O(n) work & space GPU implementation by Harris et al. (2007)
- Scan and segmented scan by Sengupta et al. (GH07)
- Vector-based (segmented) scan by Dotsenko et al. (ICS08)
- Warp-based (segmented) scan by Sengupta et al. (NV Tech Report 08 – used in CUDPP)

Applications of Scan

- Scan is a simple and useful parallel building block for many parallel algorithms:
  - radix sort
  - quicksort (segmented scan)
  - String comparison
  - Lexical analysis
  - Stream compaction
  - Run-length encoding
  - Polynomial evaluation
  - Solving recurrences
  - Tree operations
  - Histograms
  - Allocation
  - Etc.
- Fascinating, since scan is unnecessary in sequential computing!

Application: Stream Compaction



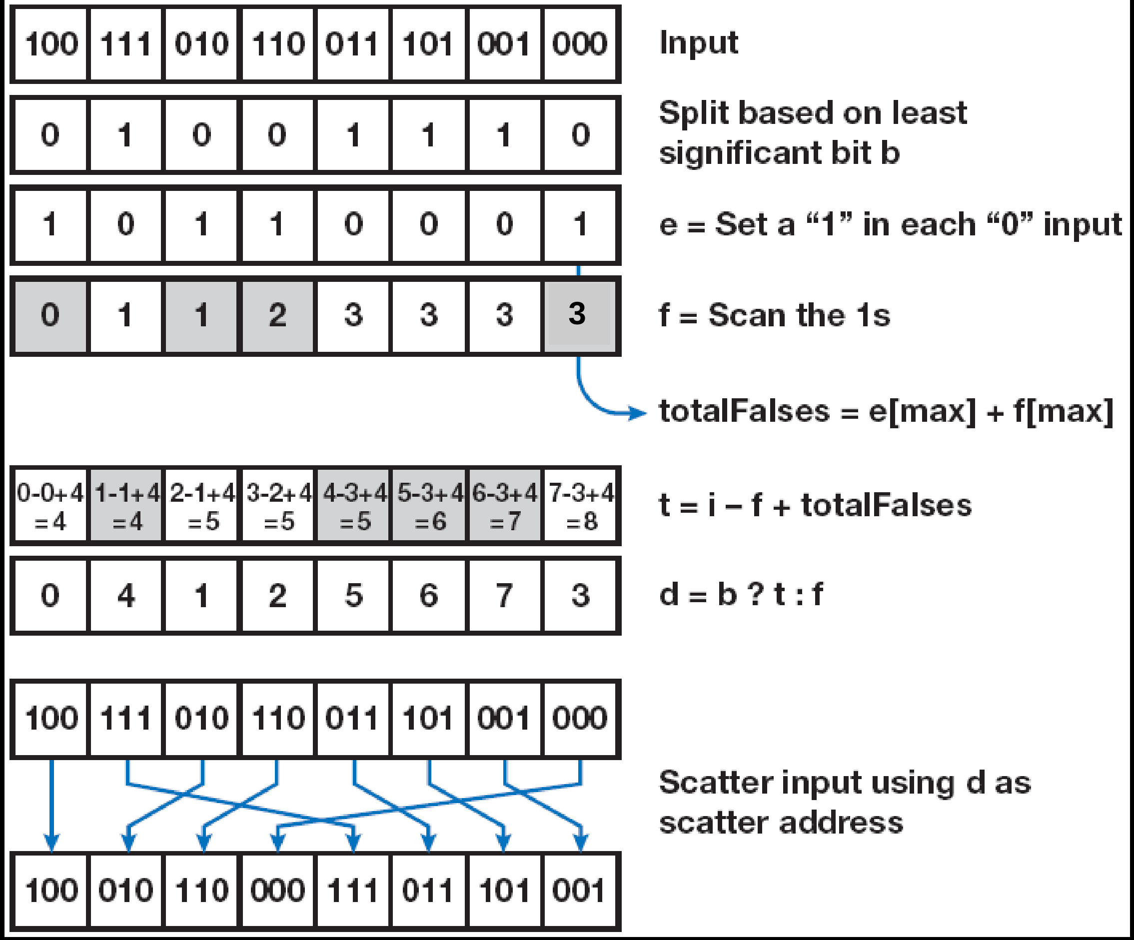
1M elements:
~0.6-1.3ms

16M elements:
~8-20ms

Perf depends on # elements retained

Harris, M., S. Sengupta, and J.D. Owens. "Parallel Prefix Sum (Scan) in CUDA". *GPU Gems 3*

Application: Radix Sort



- Perform split operation on each bit using scan
- Can also sort each block and merge
  - Slower due to cost of merge
- CUDPP Radix sort similar, but more sophisticated & efficient
  - See Satish et al. 2009

Application: Summed Area Tables

- Each pixel in SAT is the sum of all pixels below and to the left
- Can be used to perform box filter of arbitrary radius per pixel in constant time
  - Crow, 1984
  - Hensley, 2006 (O(n log n) scan)

- Easy to compute with scan
  - Scan all rows, then all columns
  - Transpose in between and scan only rows
  - GPU can scan all rows in parallel

- Scan all rows of 1024x1024 image in 0.85 ms
  - Build summed area table in 3.5 ms
  - 6 scans, transpose, (de)interleave RGBA

Segmented Scan

Segment Head Flags	0	0	1	0	0	1	0	0
Input Data Array	3	1	7	0	4	1	6	3
Segmented scan	3	1	7	0	4	1	6	3

- **Segmented scan enables another class of parallel algorithms**
  - **Parallel quicksort**
  - **Parallel sparse matrix-vector multiply in CSR format**

- **Sengupta, S., M. Harris, Y. Zhang, and J.D. Owens. "Scan Primitives for GPU Computing".** ***Proceedings of Graphics Hardware 2007***
- **Sengupta, S., M. Harris, M. Garland. "Efficient parallel scan algorithms for GPUs". NVIDIA Technical Report NVR-2008-003, December 2008**

CUDPP Impact

- CUDPP used for multiple research projects
  - At UC Davis, NVIDIA, and elsewhere
- 15+ research papers (and counting) published that use CUDPP
  - http://cudpp.googlecode.com/svn/trunk/cudpp/doc/html/cudpp_refs.html
  - Increasing number of papers using CUDPP that CUDPP developers didn't know about until publication
- Provides template for what good libraries should provide
  - Not just code but documentation, examples, unit tests, performance tests, etc.
- CUDPP 1.1 750+ downloads

Related Libraries: Thrust

- Thrust: CUDA parallel algorithms C++ template library
  - Many of the same algorithms included in Thrust and CUDPP
  - Different design goals:
    - Thrust designed for programmer productivity
    - CUDPP designed for high performance
  - Code using Thrust must be compiled with NVCC
    - CUDPP functions can be called from code compiled by other compilers, and even code written in other languages
  - Thrust has many container classes that ease handling of CPU-GPU shared data

- http://code.google.com/p/thrust

Related Libraries: cusp

- A CUDA library for sparse linear algebra graph computations
- CUSP uses highly optimized sparse matrix-vector multiplication code
  - Likely more efficient than CUDPP for these operations

- http://code.google.com/p/cusp-library/

UC Davis Sponsors

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