Update on Angelic Programming
synthesizing GPU friendly parallel scans

Shaon Barman, Sagar Jain, Nicholas Tung, Ras Bodik
University of California, Berkeley
Angelic programming and synthesis

Angelic programming:
- An oracle invents an example execution
- Programmer generalizes example to an algorithm

Results:
- Entanglement: a tool to help with algorithm discovery

Synthesis with sketching:
- Sketch is a template synthesized into an implementation
- The resulting program meets a functional specification

Results:
- Sketching generates algorithm variants (for autotuning)
Why scans?

Many practical algorithms use scans [Blelloch ’90]

- lexically compare string of characters; lexical analysis
- evaluate polynomials
- radix sort, quicksort
- solving tridiagonal linear systems
- delete marked elements from an array
- search for regular expressions
- tree operations
- label components in two dimensional images
- dynamic programming (see Evan Pu’s poster)

Many problems are sums with some assoc operator
Implementing scans

N = 8

instance of parallel scan algorithm

its abstract visualization
SIMD execution of scan algorithms
Hierarchical execution of scans algorithms
The workflow (talk outline)

- space of all algorithms
  - all networks that meet some constraints

- instance of the algorithm
  - a specific network for a fixed input size

- program of the algorithm
  - works for arbitrary input size

- functional variants of the algorithm
  - forward/backward x inclusive/exclusive

- segmented scan
  - for various segment representations

- optimized scan
  - bank conflict avoidance
Finding an example network

A textbook (clean, regular) instance of the algorithm is all we need to define the algorithm.
How do we find such networks?

Ask angels how to do parallel scan in \(O(\log n)\) time

```plaintext
N = 16
ops = 0
for step = 1 .. 2*\log(N)
  for r from 0 to N-1 in parallel
    if (!!)
      x[r] = x[r] + x[r-!!]
    ops += 1

assert x is a prefix sum
assert ops <= 2N
```
Problem with angelic programming

Synthesizer creates irregular networks
Attempt 1: find a regular pattern

- Ask angels to generate all networks
- Find one that is regular
- Manually examine each network for regularity
- Too many networks (possibly thousands)
Attempt 2: Functional decomposition

- Look at all networks
- Find in them the function they compute
- These are the subcomputations
- Example network:
  - The right functional view make them the same
Entanglement

- Entanglement occurs when angels coordinate
- We use this coordination to partition the angels
  - No coordination across partitions
- Unentangled angels = subcomputations
Building a regular pattern

Examining each partition leads to the BK pattern
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for d in 1 to log N
  forall i in 1 to N
Generalize Examples to Programs

Input

Output

```plaintext
offset = 1
for step = 1 .. log(N)
    for i from 0 to N-1 in parallel
        if((i+1)%2*offset)
            a[i] = a[i] + a[i - offset]
        offset = offset * 2
    offset = offset / 2
for step = 1 .. log(N)
    for i from 0 to N-1 in parallel
        if((i+1)%2*offset && (i + offset) < N)
            a[i + offset] = a[i] + a[i + offset]
```
Generalize Examples to Programs

Generalize into recursive program
Sketching

Input:
- Functional specification (e.g., compute the scan function)
- Sketch (a program template)
- Constraints (e.g. assertions)

Output:
- Program that meets the spec and the constraints

Hello world example of sketching:
Spec : \( x + x \)
Sketch : \( \Box \star x \)
Output: \( 2 \star x \)
From BK instance to BK code

Input:
- Functional specification (Sequential Scan)
- Sketch
  
  for step = 1 .. log(N)
  for i from 0 to N-1 in parallel
    if(☐)
      a[☐] = a[i] + a[☐]
  
- Constraints -- Execute like the BK(16) example

Output:
- SIMD program for BK on any (or many) N
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- Segmented scan
  For various segment representations

- Optimized scan
  Bank conflict avoidance

```python
for d in 1 to log N
  forall i in 1 to N
```
Forward to Backward

Input:
- **Forw Spec**: \( a[i] = a[i] + a[i-1] + \ldots + a[0] \)
- **Back Spec**: \( a[i] = a[n-1] + a[n-2] + \ldots a[i] \)

Output:

```plaintext
for step = 1 .. log(N)
    offset = offset / 2
    for i from 0 to N-1 in parallel
        if((i+1)%2*offset == 0 && (i + offset) < N)
            a[i + offset] = a[i] + a[i + offset]

for step = 1 .. log(N)
    offset = offset / 2
    for i from 0 to N-1 in parallel
        if(i%2*offset == 0 && (i - offset) >= 0)
            a[i - offset] = a[i] + a[i - offset]
```
Segmented Scans

Input is divided into segments and scan is performed for each of the segments.
Segmented Scans

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Segmented Scans

- Segments can be represented in various ways:
  - Bit mask – \(\{1, 0, 0, 1, 0, 0, 1, 0\}\)
    - 1 denotes starting point of each segment.
  - Header Pointers – \(\{0, 3, 6\}\)
    - Each entry denotes index corresponding to start of each segment.
  - And many more.

- We can synthesize ‘bit mask’ program from an unsegmented implementation.

- Further, we would like to derive implementations from one representation to other representations.
Bank conflict avoidance

Input:

- Functional specification (i.e., compute scan)
- Sketch (deterministic BK$_2$ with array re-indexing)
- Constraint – minimize bank conflicts

One approach to bank conflict optimization for BK$_2$ involves remapping array indices, so distinct memory accesses are actually handled in parallel.

We have synthesized [injective] reordering functions as shown below. Synthesis takes approximately 2 minutes.
Bank conflict avoidance

We were able to sketch another algorithm, the BK\textsubscript{3} circuit, in which each thread processes 3 elements [additions] instead of 2, and the recurrence operates on every 3 elements from the previous step.

The recurrence operates on every 3 elements, not every 2.
Bank conflict avoidance

The BK$_3$ circuit showed a 14% performance improvement over the BK$_2$ circuit on a GTX 260, though it is currently outperformed [on that chip] by nVidia's non-work-efficient scan kernel.

Experimentation has shown that padding the array does not help much, since we have to calculate the new indices.
There’s more...

• Come visit my poster!
  – Low level CUDA model that can help synthesize programs to avoid typical RW hazards and syncthreads misuse
    • The BK$_3$ sketch was written with this model
  – Language support ("instrumentation") to facilitate counting bank conflicts, or checking RW hazards
  – Histogramming work
  – Ongoing Scala work for a nicer frontend language
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