# Evaluation of Parallel Hashing Techniques

Rajesh Bordawekar
IBM Thomas J. Watson Research Center

bordaw@us.ibm.com

# Problem Statement

To implement an efficient hash table on GPU to insert and query data in parallel, and evaluate its performance against the state-of-the-art CUDPP hash.

# Outline

- Motivation
- Existing Approaches
- Requirements
- New proposal
- Experimental Evaluation
- Summary

# Motivation

- Hash Table: a fundamental indexing data structure with uses in multiple domains, e.g., data management, graphics, text analytics, bio-informatics,..
- Memory-bound workload characterized by random memory accesses
- GPU's impressive device memory bandwidth makes it a good candidate as an execution platform
    - Can be used as an off-load accelerator or the primary processor

# Design Goals

- Index large datasets
- Exploit massive data-parallelism of the GPU for probing and querying
    - Large thread blocks and large number of threads
- Improve  data access locality while querying and insertions
- No additional data structure for querying
- Minimize the use of atomic operations
- High load factor without excessive space utilization (e.g., bins)

# Related Approaches

- Probing based approaches (e.g., linear, quadratic)
- Cuckoo Hashing and its variants [Pagh, Rodler 01]
- Robin-hood Hashing
- Hop-scotch Hashing [Herlihy, Shavit, Tzafrir 08]

# Cuckoo Hashing

- Eviction-based conflict resolution
- Uses multiple hash tables with distinct hash functions
  - Upon conflict, i.e., position[y]=h(x), x is stored at position[y], and a new location for y is selected using g(y)
  - Process continues until an empty spot is found
- For querying, a fixed number of probes are required
- A variant, Robin-hood hash, uses eviction based on entry age

# Hop-scotch Hashing

- Tries to store conflicted entries closer to the conflict location (called Hop region)
  - While querying, items that map to the same location can be fetched using few consecutive cache lines
  - Common sizes of hop region (hop distance) 4 or 32
- Key idea: Create space in the hop region by repeated exchange of empty space with allocated entries
  - Exchange always happens within hop distance
- Uses hop-map to store locations of entries within hop region

# Cuckoo Hashing on GPUs

- Cuckoo Hash [Alcantara 09,11] (released as a part of CUDPP)
  - Coherent Parallel hashing[Garcia et al, 11]  uses the Robin-hood hashing approach
- CUDPP hash version uses 4 hash functions and a constant size stash (100 elements)
  - Uses 1.25*N space
  - 64 Threads per block
  - At most 5 accesses for querying

# Cuckoo Hashing Properties

- Requires fixed, small number of accesses while querying
- Requires least amount of space among different hashing approaches
- Chained evictions may not terminate
- Cuckoo hash can not consider data locality
- Needs to use multiple hash functions to improve load factor
- Requires smaller-sized thread blocks
- Number of atomic operations not dependent on input data size

# Hop-Scotch Hashing Properties

- Multiple conflicted values lie within the hop-scotch region
- May require multiple evictions
- Chained evictions may not find empty slots
- Hop-scotch hash requires additional data structure for querying
- Number of atomic operations not dependent on input data size

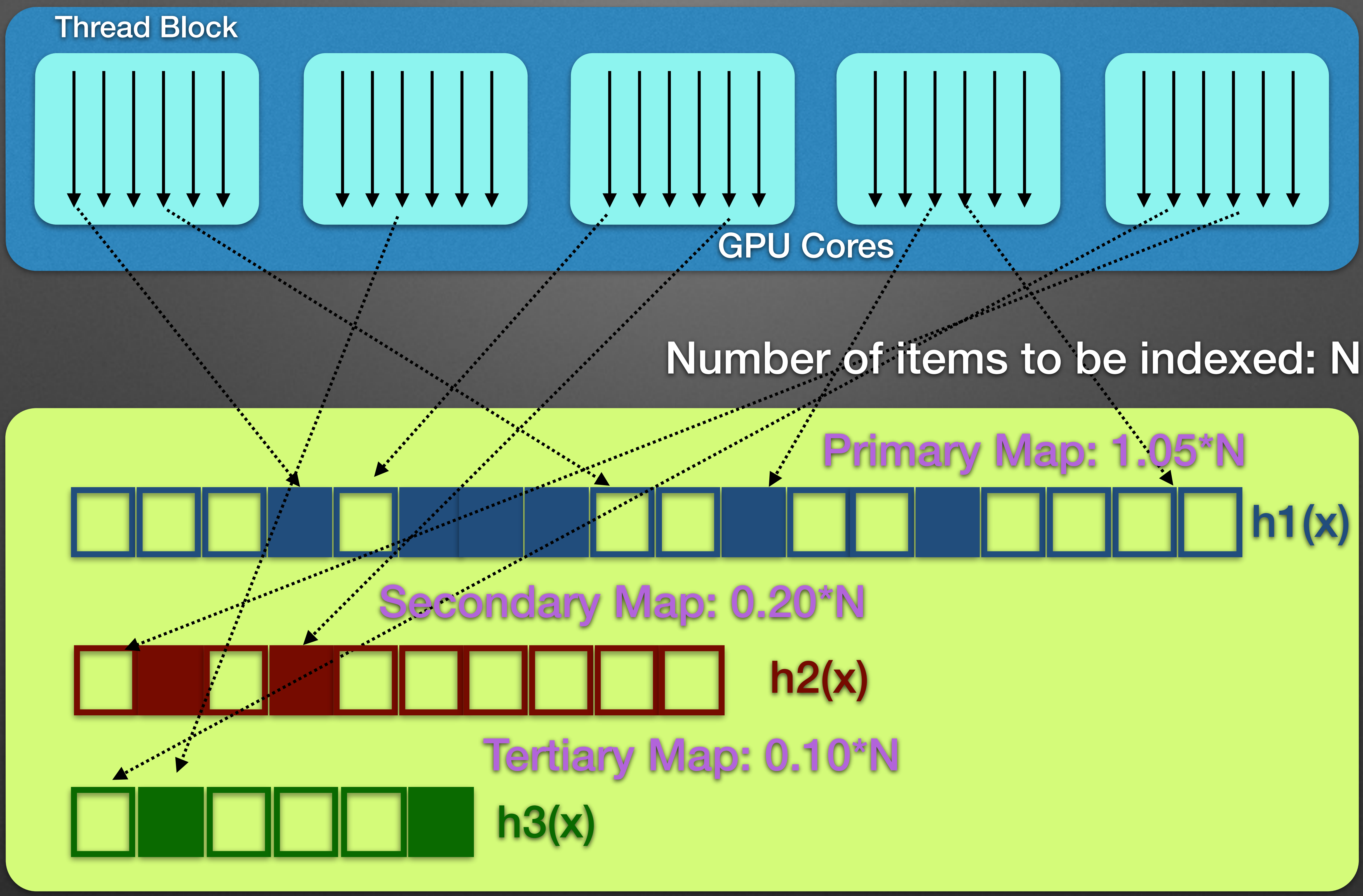
# Multi-level Bounded Linear Probing

- Multiple hierarchical (in practice, 2 or 3) hash maps of varying sizes
  - map size decreases as the map level (depth) increases
  - can be extended to support buckets
- Each map uses a different universal hash function
- Linear probing on conflicts: search *fixed-sized* regions for empty spaces
  - Probe region size multiple of 4 bytes or cache line size (if greater than 128 bytes)
  - Size of the region varies per map level; for higher levels, probing region is small
- Lock-free concurrent implementation using 32-bit atomic CAS

# Design Alternatives

- Two-level hash table with two maps, each with its own hash function
  - secondary map size: 0.25*N
  - Primary probe region: 4, secondary probe region: 256
- Two-level hash table with 2 maps; two-element buckets associated with the smaller map
  - secondary map size: 2*0.25*N
  - Primary probe region: 4, secondary probe region: 32
- Three-level hash table with 3 maps
  - secondary map size: 0.2*N, tertiary map size: 0.1*N
  - Primary probe region: 4, secondary probe region: 8, tertiary probe region: 8

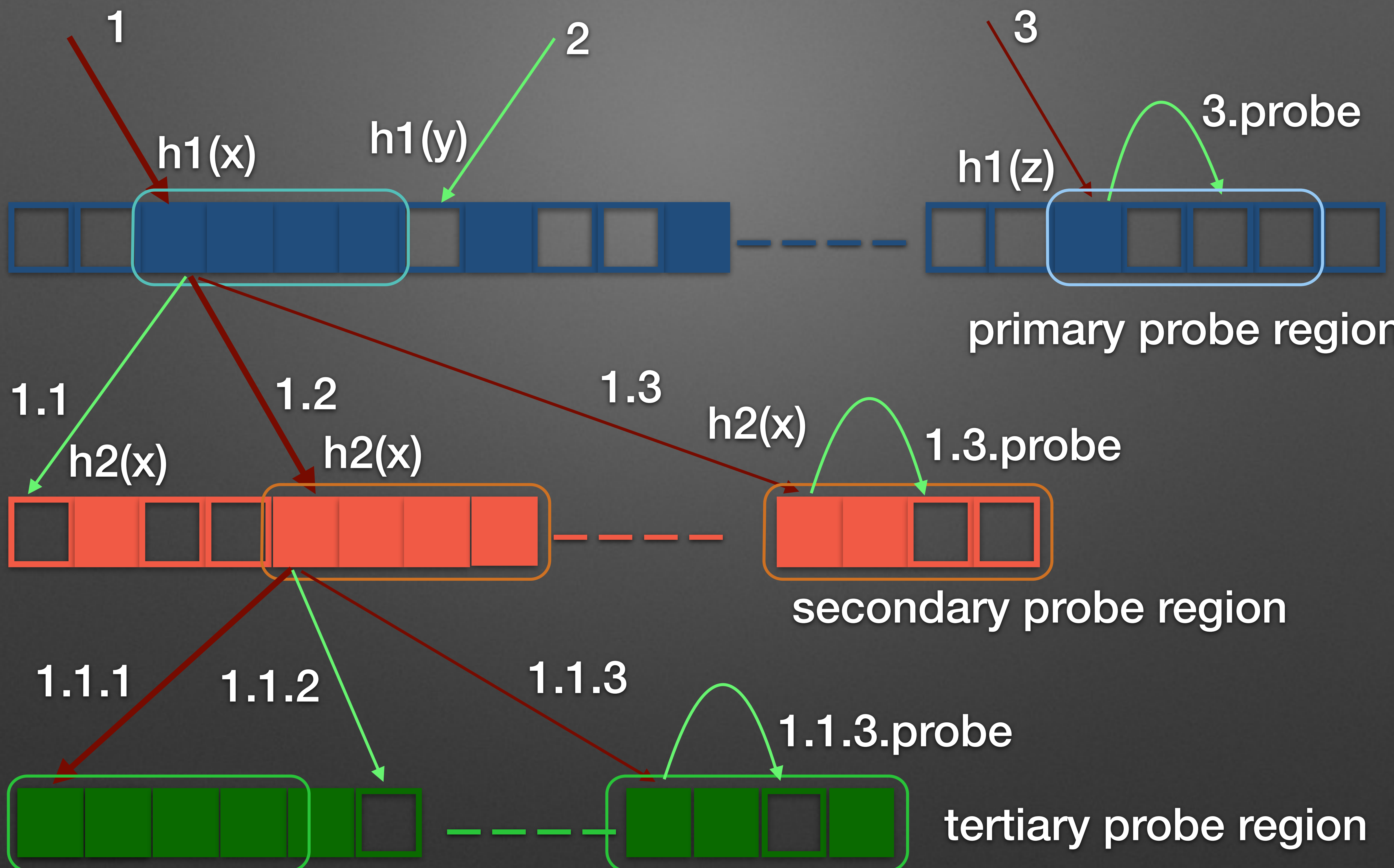
# A Three-level Hash Table




GPU Device Memory

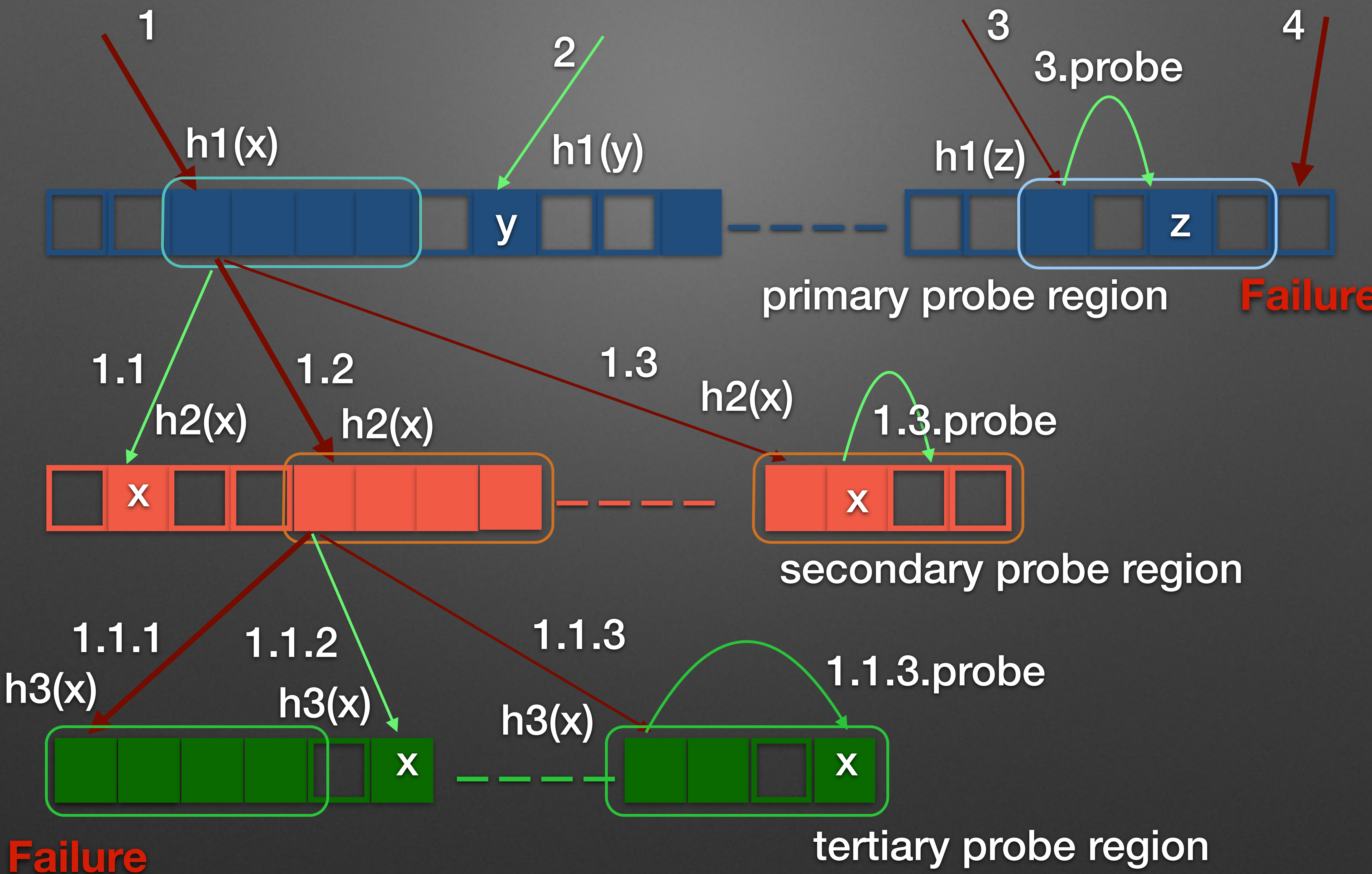
IBM Research

# Insertion Process




size(primary probe region) <= size(secondary probe region) < size(tertiary probe region)

# Query Process




IBM Research

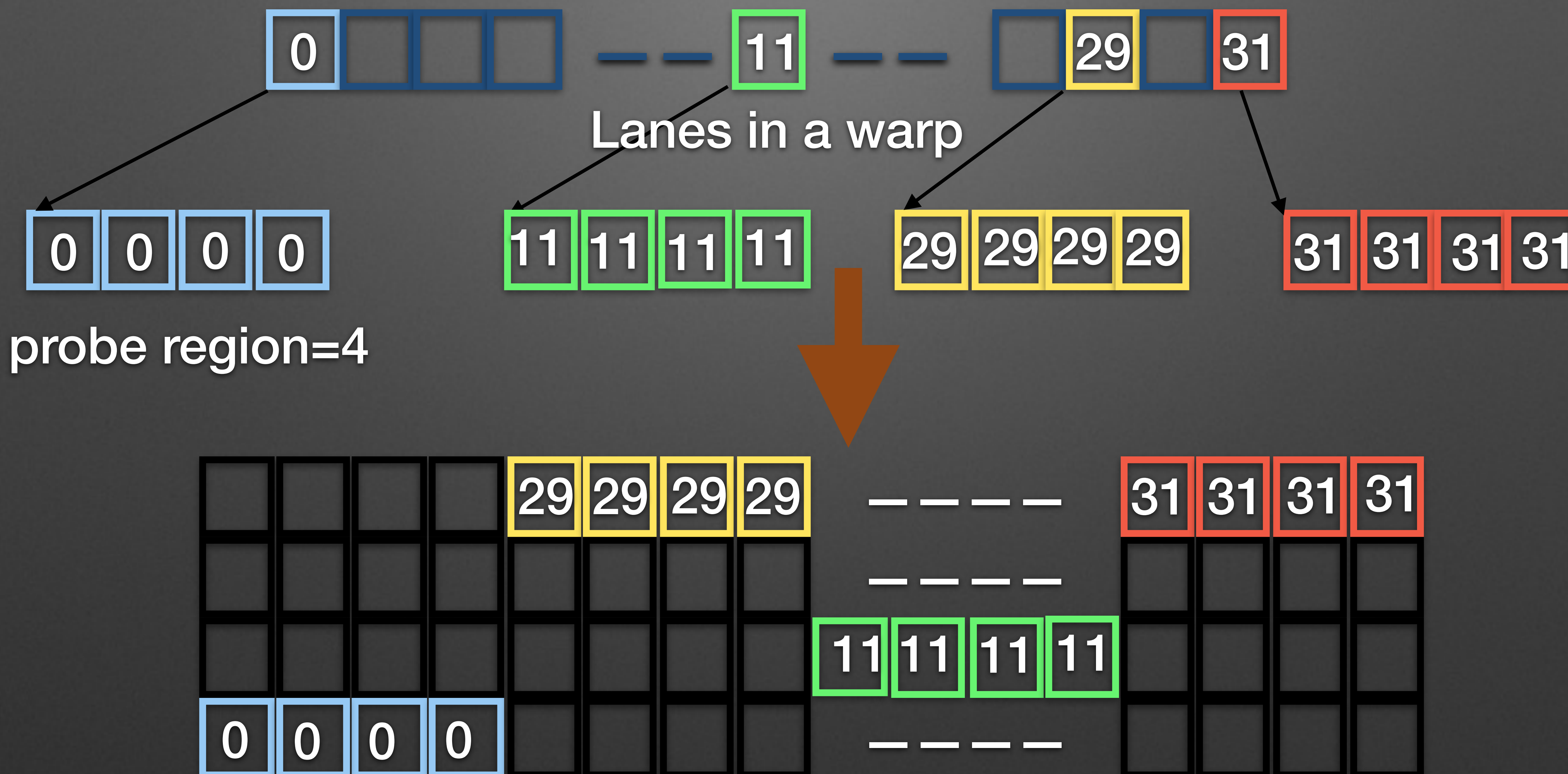
# Implementation Details

- Works for 32-bit keys and values
- Keys and values stored separately. Keys locked using 32-bit atomicCAS()
- Uses universal hash functions
  - hash(x) = ((constant_a * x + constant_b) mod P) mod Size
  - Each level uses a different hash function
- Size of the thread blocks varies from 32 to 512. Number of thread blocks is not limited.

# Advantages of the approach

- Overall space utilization similar to that of cuckoo hashing, with higher load factor
- Only uses fast single-precision atomic CAS operations
  - Number of CAS operations in the order of input data items (N)
- Multiple levels enable bounded probing and reduce the size of bounded probe region
  - Probe region sizes: (4, 256) for two levels, (4, 8, 8) for three levels
- Probe region size enables hardware coalescing and exploits locality during insertion and querying
- No restrictions on the number of threads in the thread block
- Enables data-parallel implementation of querying functions

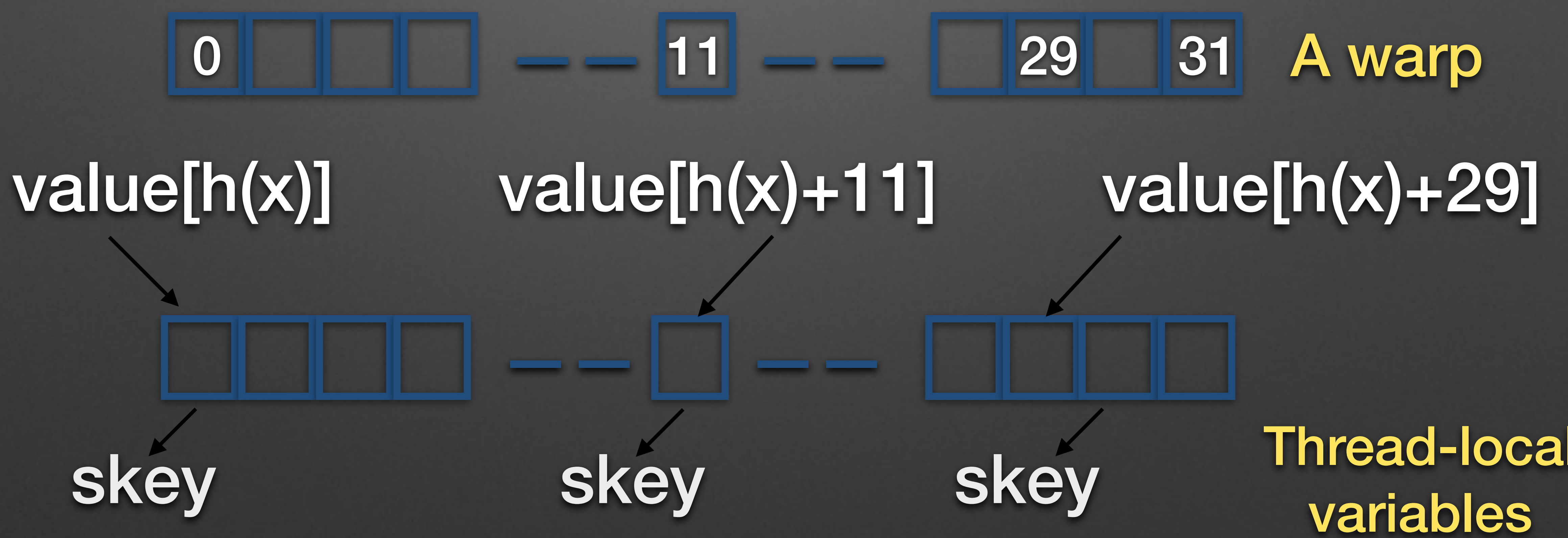
# Device Memory Access Optimizations




4 lanes fetching four consecutive elements

# Data-parallel Querying

1. hasKey() on input key, x, probe region=32
2. Each warp lane “i” fetches value at h(x)+i
3. Use warp vote function __any()




Each warp lane executes __any(x, skey)

# Experimental Setup

- Experiments executed on Tesla K40c using CUDA 5.5
- Compared against Cuckoo Hash implementation from CUDPP-2.1(Oct 2013)
  - ./cudpp_hash_testrig -basic -n{size}
  - Compared build and 0% failure times
  - Using the same random datasets generated via CUDPP test suite
- Evaluated two-level, two-level with 2-element buckets, and three-level hash functions
  - Two-level: Primary probe region=4, secondary probe region=256
  - Two-level Bucketing: Primary probe region=4, secondary probe region=32
  - Three-level: Primary probe region=4, secondary/tertiary probe region=8
- 256 threads in a block, primary map=1.05N, secondary map=0.25/0.20, tertiary map=0.1N

# Initial Results: Hash Table Build

Number of Key-Value Pairs (Time in ms)

| METHOD | 1 M | 10 M | 16 M | 32 M | 64 M | 128 M | 256 M |
|---|---|---|---|---|---|---|---|
| TWO LEVEL | 3.1 | 38.7 | 62.6 | 126.4 | 270.9 | 614.6 | 2040 |
| TWO LEVEL BUCKET | 3.26 | 40.6 | 65.6 | 132.5 | 270.8 | 621.6 | 2220 |
| THREE LEVEL | 3.28 | 40.7 | 65.8 | 132.6 | 271.4 | 618 | 2100 |
| CUDPP | 5 | 57.5 | 88.7 | 177.9 | 354.3 | 700 | 1500 |

# Initial Results: Hash Table Querying

Number of Key-Value Pairs (Time in ms)

| METHOD | 1 M | 10 M | 16 M | 32 M | 64 M | 128 M | 256 M | |
|---|---|---|---|---|---|---|---|---|
| TWO LEVEL | 0.858 | 10.6 | 17.1 | 35 | 153 | 426 | 982.8 | hasKey() |
| THREE LEVEL | 0.782 | 10.7 | 17.5 | 37.6 | 194.8 | 534 | 1210 | |
| TW0 LEVEL | 1.5 | 17.6 | 28.4 | 84.7 | 265.5 | 651.4 | 2010 | |
| THREE LEVEL | 1.4 | 18 | 29.5 | 93.9 | 303.8 | 731 | 1650 | getValue() |
| CUDPP | 1.5 | 16.7 | 26.8 | 67.7 | 191.9 | 442 | 964 | |

Two types of queries: hasKey() and getValue()

# Discussion

- In all cases, around 85% of data fits in the primary map
- Large probe regions have no effect on performance
- Reducing thread block size reduces build performance slightly; no impact on query performance. Using 512 threads leads to no improvement
- Data-parallel querying and probe region optimizations not effective
- For large data sets, build and query performance affected by non-coalesced write accesses and larger number of read accesses
    - Cuckoo Hashing invokes a fixed, smaller number of read accesses

# Summary

- Competitive performance to cuckoo hashing
  - Build-phase better than cuckoo hashing, query performance slightly lower
  - Similar space utilization (1.25 to 1.30*N)
  - Non-coalesced write accesses and conditionals affect the performance
- Further optimizations needed to reduce the memory access costs
  - Warp-level coalescing, co-locating data and values
- Detailed analysis and multi-core CPU implementation underway

# Insertion Process

- For input value x, first compute position in the primary map using the hash function h1, *pos= h1(x)*
  - If map[pos] == 0, return SUCCESS (case 2)
  - if map[pos] !=0, find empty slot in the primary probing region (cases 1 and 3)
    - If empty slot found, return SUCCESS (case 3.prob)
    - If no empty slot found, proceed to the secondary map (case 1)
- Compute position in the secondary map using the second hash function h2, *pos2=h2(x)*
  - repeat the process for insertion for the secondary map, but using the secondary probing region (cases 1.1, 1.2, 1.3)
  - If no empty slot found, proceed to the tertiary map (case 1.2)
- Compute position in the tertiary map using the third hash function h3, *pos3=h3(x)*
  - *repeat the process for insertion for the tertiary map, but using the tertiary probing region (cases 1.1.1, 1.1.2, 1.1.3)*
  - *If no empty slot found, proceed to the tertiary map (case 1.1.1)*
- *size(primary probing region) <= size(secondary probing region) < size(tertiary probing region)*

IBM Research

# Query Process

- For input value x, first compute position in the primary map using the hash function h1, *pos= h1(x)*
  - If map[pos] == x, return SUCCESS (case 2)
  - if map[pos] !=0, find used slots in the primary probing region (cases 1 and 3)
    - If one of the values at these slots, matches x, return SUCCESS (case 3)
    - If there is no match, proceed to the secondary map (case 1)
  - else if map[pos] == 0, return FAILURE
- Compute position in the secondary map using the second hash function h2, *pos2=h2(x)*
  - repeat the process for querying the secondary map, but using the secondary probing region (cases 1.1, 1.2, 1.3), return SUCCESS on a match (cases 1.1, and 1.3)
  - If there is no match, proceed to the tertiary map (case 1.2)
- Compute position in the tertiary map using the third hash function h3, *pos3=h3(x)*
  - *repeat the process for querying the tertiary map, but using the tertiary probing region (cases 1.1.1, 1.1.2, 1.1.3), return SUCCESS on a match (cases 1.1.2, and 1.1.3)*
  - If there is no match, return FAILURE *(case 1.1.1)*
- *Return the corresponding values when invoked via GetValue(key, value)*