SEMANTIC LOCALITY AND ITS USAGE IN MEMORY PREFETCHING

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The premise

- Memory access streams often exhibits some regularity
  - Can be used for prefetching, smart caching, address prediction, task scheduling, etc.. But how do we identify them?
- Current memory systems (caches, prefetchers) are most efficient with tempo-spatial locality
- However, many algorithms require linked data structures or contextual linking (e.g. linked data structures)

The cache-friendliness dilemma

- In many cases, performance drives programmers to layout data such that it benefits from spatial cache layout
  - Graphs as arrays or adj. matrices
  - Sparse matrix coding
- The result is non-intuitive, complex code

- Some structures are less amenable to cache-friendly restructuring

- Can we capture semantic structure of data regardless of programming model and data structure layout?

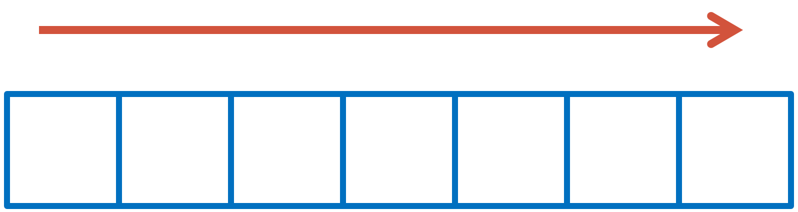
Semantic vs. Spatial locality

- Grid structured memories are tuned for adjacent accesses
  - Consequently, we aim to map data to adjacent locations
- We are used to thinking of locality as a property of space
  i.e. ***Spatial Locality***
- But data recurrence (locality) is inherent in program semantics and is also common in irregular data structures
- Spatial locality is a manifestation of ***Semantic Locality***

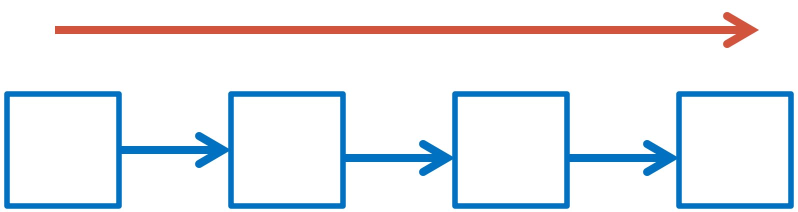
Identifying program semantics

The following are *semantically* identical

```
for(i=0; i++; i<N)
  if(array[i].key==key)
    return array[i].val
```



```
while(node != NULL)
    if(node->key == key)
       return node->val;
    node = node->next;
```



But can we automatically identify semantics?

Approximate semantics with context

- Use machine context at the time of access to learn about the context of the access
  - Location of reference (IP)
  - Memory region (heap, stack)
  - Branch history
  - Performance monitors
  - …

Extract context from the code

- Programming languages (especially objective ones) have the power to tell us much about how we access memory
  - Pointers to strongly-typed data structures
  - Object sizes and internal fields organization
  - Location of reference (IP)
  - Different forms of access (e.g. in c: **[]**, *****, **->**)
  - Recognizable pointer arithmetic

- Dynamic run-time observation can fill in the rest

Example: Context through compiler hints

- Some accesses are more important than others…

```
while(node != NULL) {
    if(node->key == key)
        return node->val;
    node = node->next;
    hint_correleation(node, node->next)
}
```

Context-based access predictor

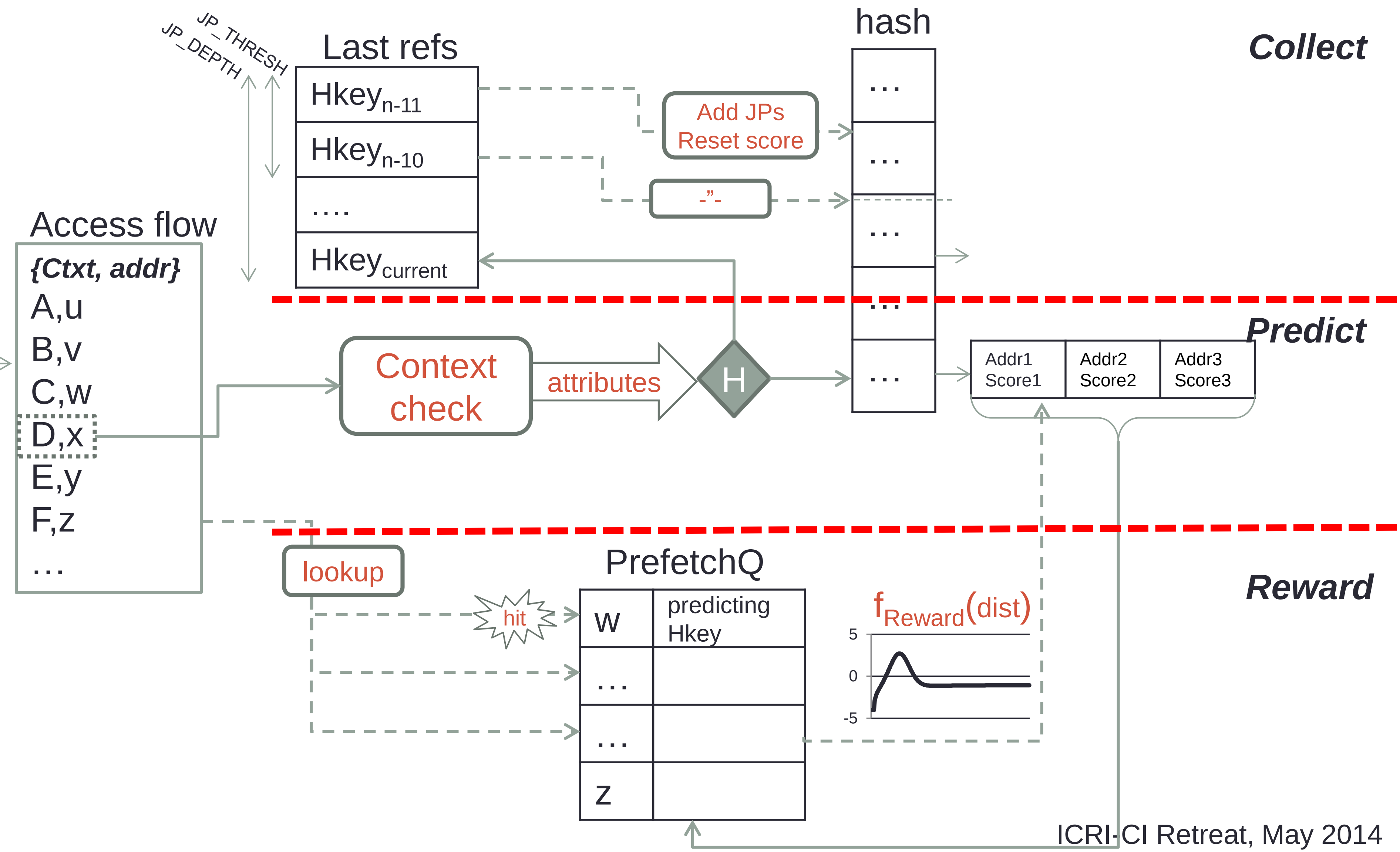
- Collecting all the context information for each access provides a massive quantity of data.
  - Need some technique to store it and find hidden patterns.

- ***Ultimate goal***: recognize recurring links between any given context-state to future access, and learn how to produce context-based prediction.
  - Bind together block, stride and irregular data semantics

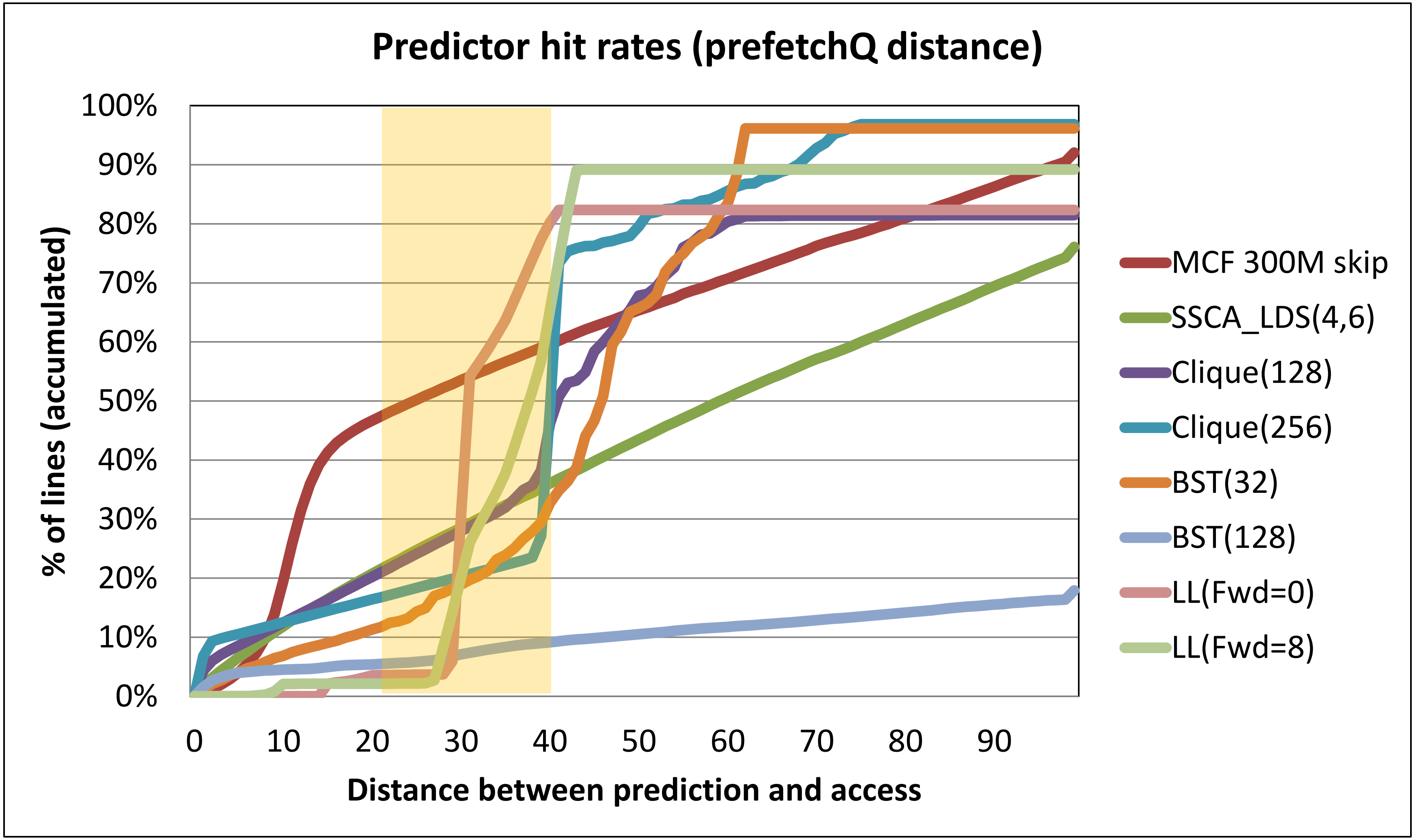
- ***First cut***: focus on irregular data semantics

Training a context-based prefetcher: A sketch

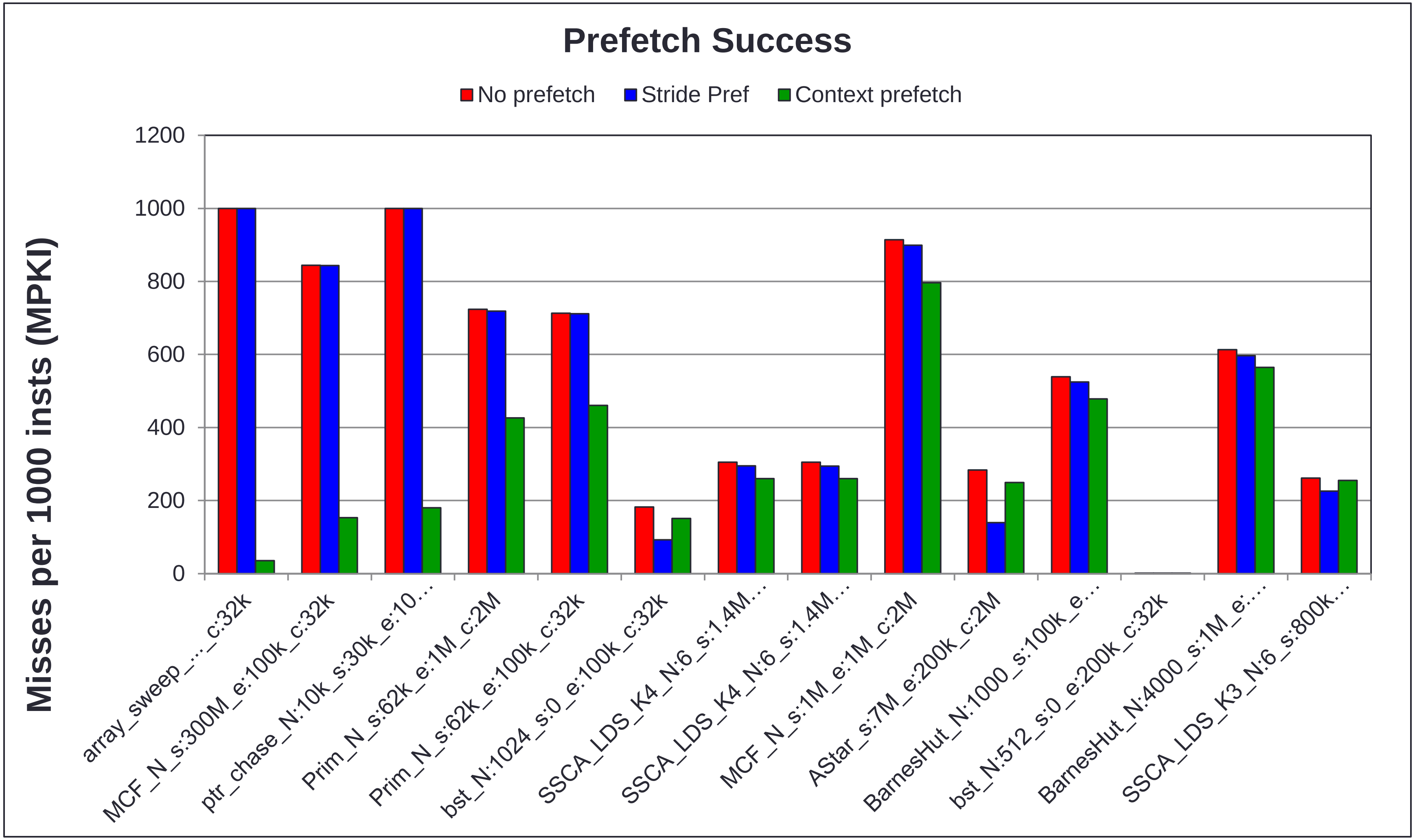
Schematic flow



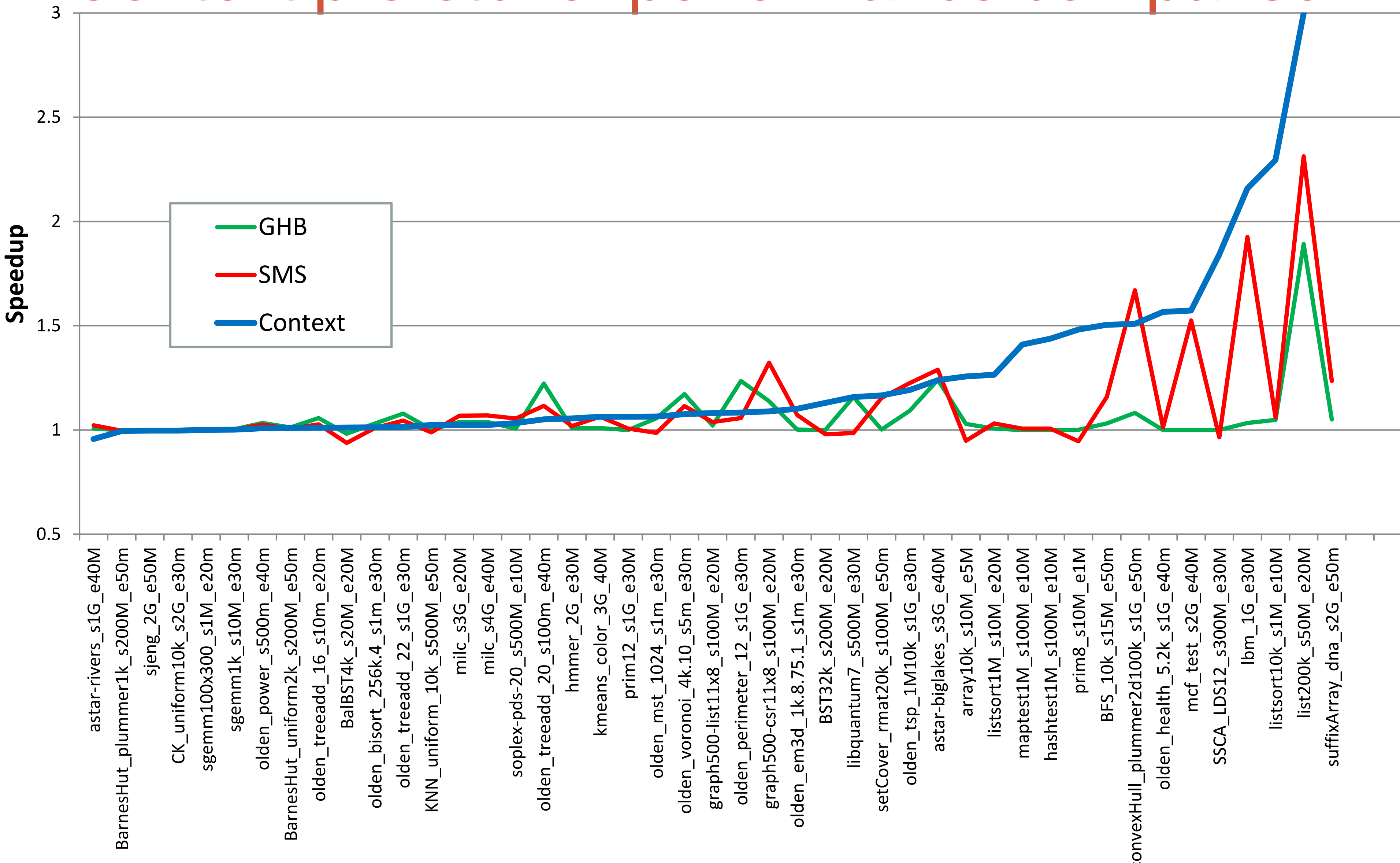
Predictor results (SW model – LearningPtr lib)



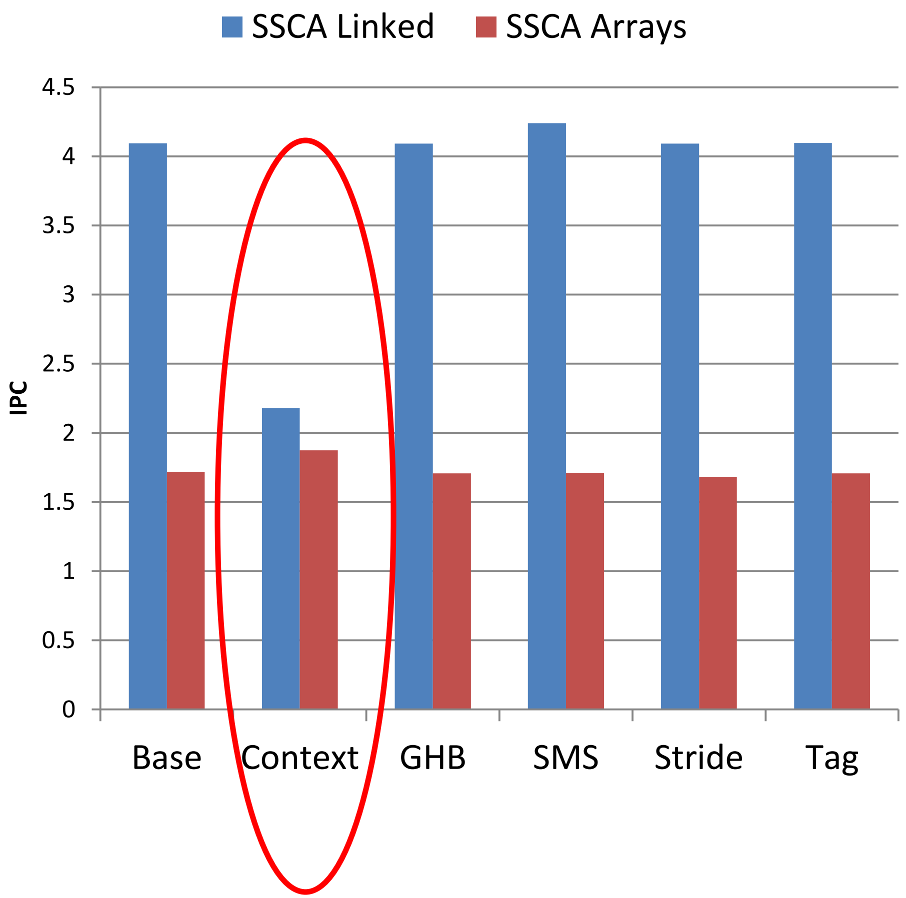
Predictor results (SW model: *LearningPtr lib*)

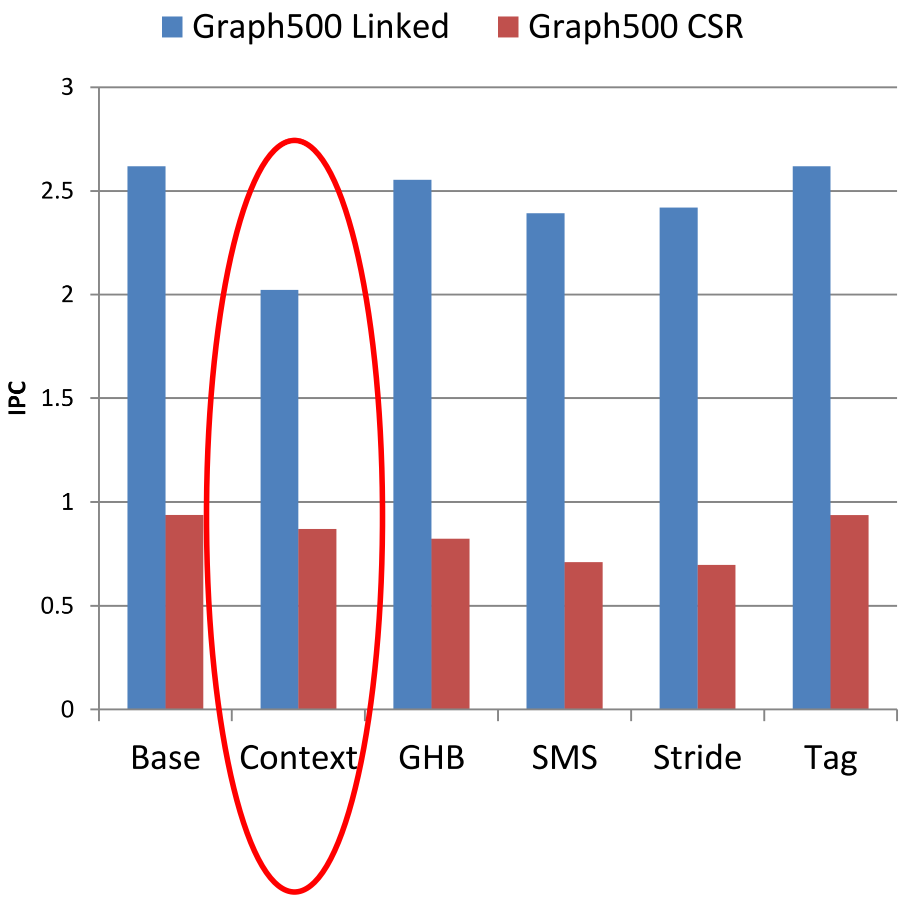


Context prefetcher performance comparison



Layout-agnostic implementation





Conclusions (so far)

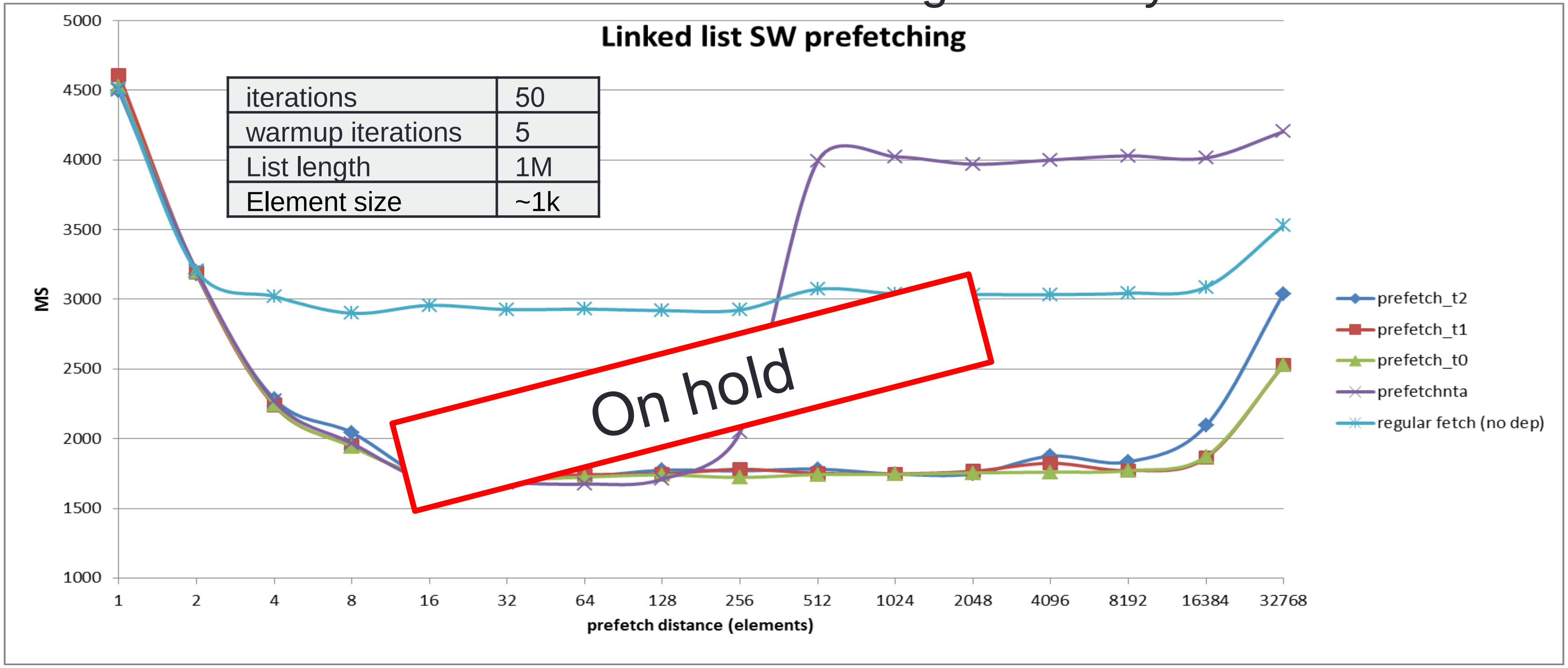
- Program semantics hold information about data correlation and association and can help performance
- …but automatically extracting program semantics is a big and open problem
- Machine state and compiler cues can help approximate data semantics
- Program/machine context, coupled with simple reinforcement learning, can help data prefetching
- We show that layout-agnostic data structures are feasible, but more research is needed before we can call it a success

QUESTIONS?

…and thank you…

Linked list lookahead potential

- Simple List traversal, Augmented using SW prefetches:
- Prefetch distance benefit limited according to locality method



- When prefetching mem-resident list through SW, hitting max potential at ~16 elements
  - This is a hard limit, reflecting shift from being latency-bound to BW-bound

PREV TEXT SLIDES

Research Track:
Semantic locality and context-based prefetching

[with Leeor Peled and Uri Weiser]

Machine Learning

- Investigating approaches similar to Contextual Multi-Armed Bandits.
  - The potential set of “actions” is as big as the effective memory space
    - Classic reinforced learning cannot be applied
  - Huge context space - hard to exploit similarities
  - Rewards are delays according to how far we attempt to predict

- Big question: how to implement in hardware…

Address prediction – basic algorithm

- For each memory access n :
  - Record current program state X_n
    - (dst_type, src_obj, access_type, ptr_offset, IP, IP-hist, addr-hist, delta, index, etc…)
  - For each m in the predictable depth range (e.g. [20-40]):
    - Push $Addr_n$ into the reference hash, with key = hash(X_{n-m})
    - Search entry at hash(X_{n-m}) for the addresses with leading score, and issue them into the predictionQ
  - Match $Addr_n$ with predictionQ.
    - On hit, update the state that created the prediction in the reference hash according to the reward function

Additional Issues

- Hash reduction -
  - Prevent overfitting and slow learning due to huge state-space
  - 2-level hashing by using partial attributes, open more on overflow
  - In the future - dynamically select best attributes
- Drop off predictorQ -
  - Update if no match by that time
- Various options for back2back double address updating
  - Do we want to predict an address that was already predicted by another context?