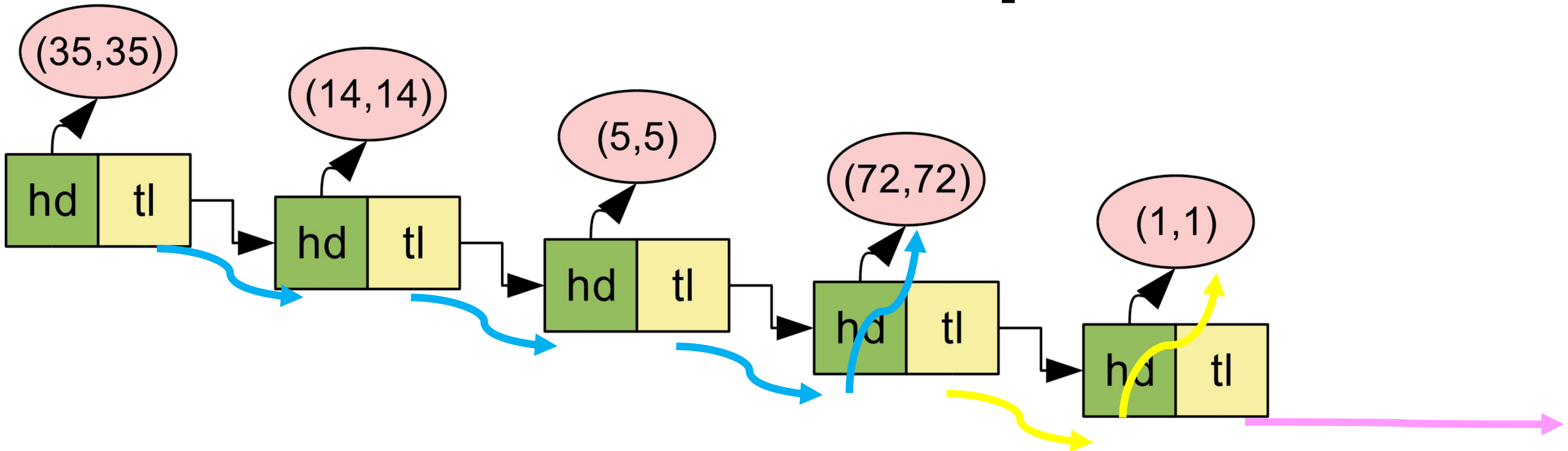
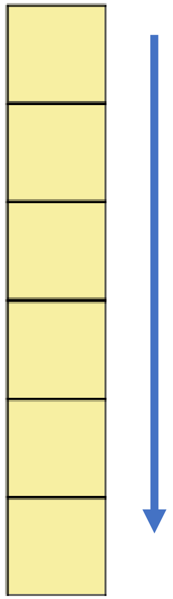
Prefetching in Functional Languages: A Hardware-Software Retrospective



Sam Ainsworth

(Based in-part on a paper with Timothy M. Jones at ISMM 2020)

Motivation: Everybody knows functional data structures are scary



Those nice prefetchable arrays are, sadly, mutable

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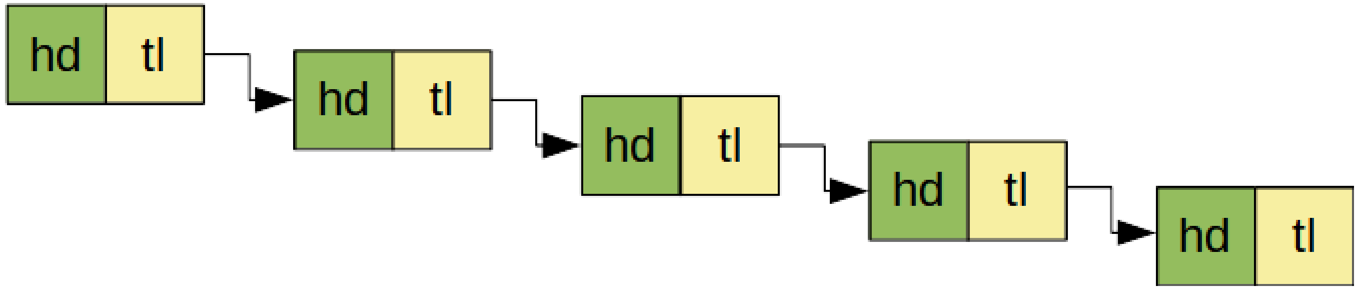
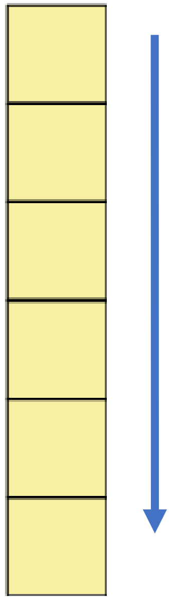
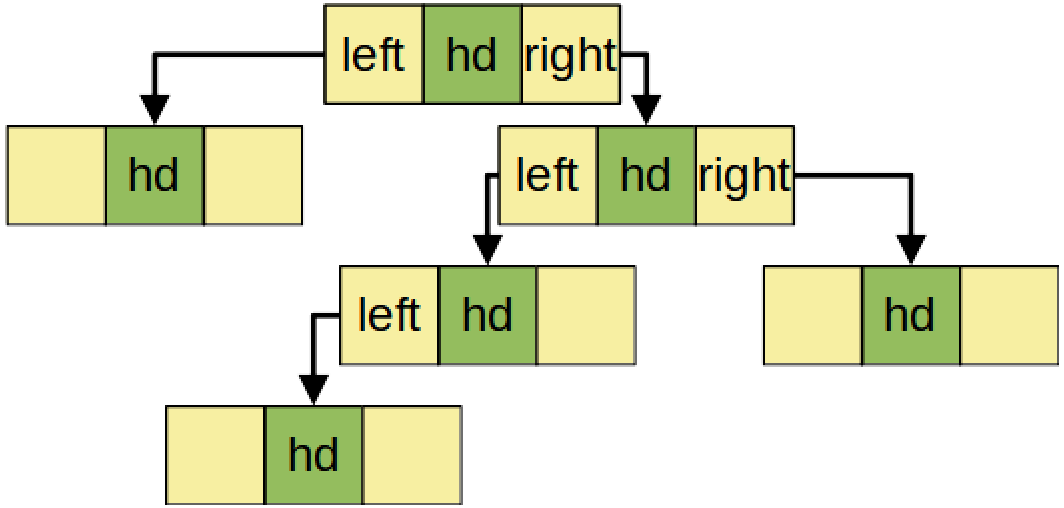


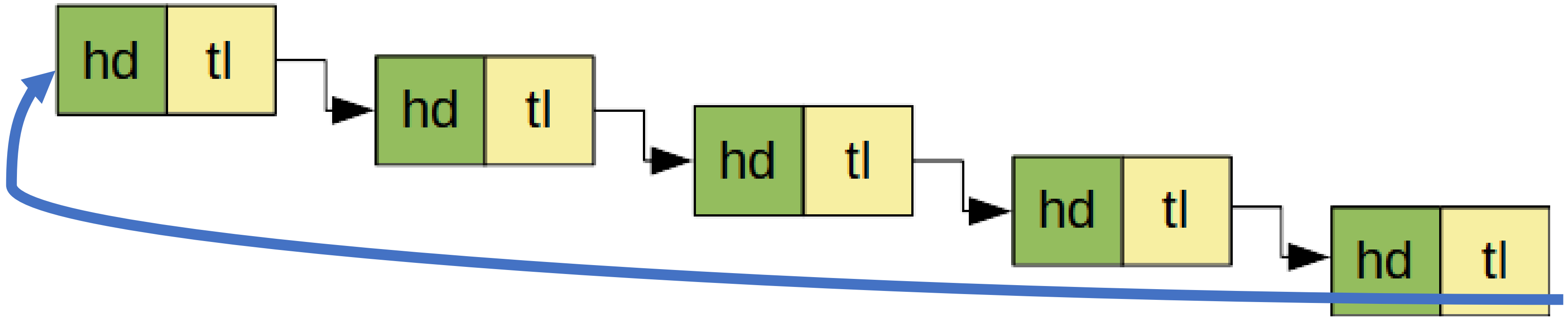


Where’s the Memory-Level Parallelism for linked lists or trees?



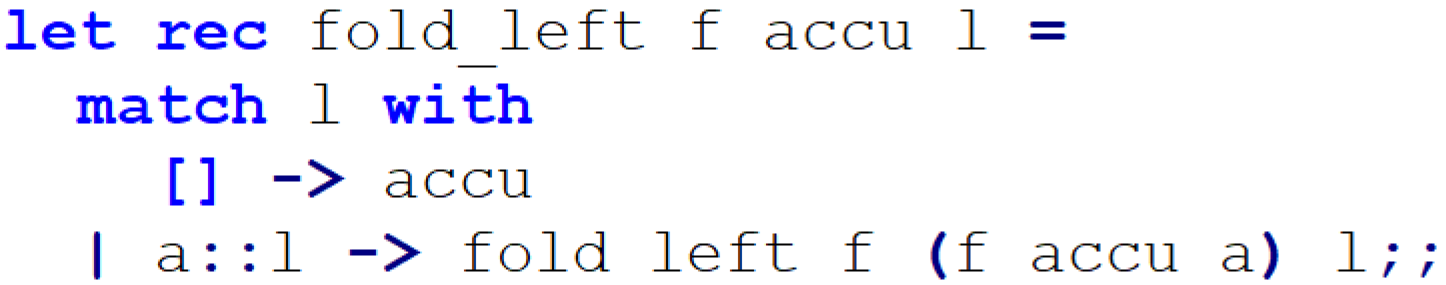
Those nice prefetchable arrays are, sadly, mutable

One answer: temporal prefetching

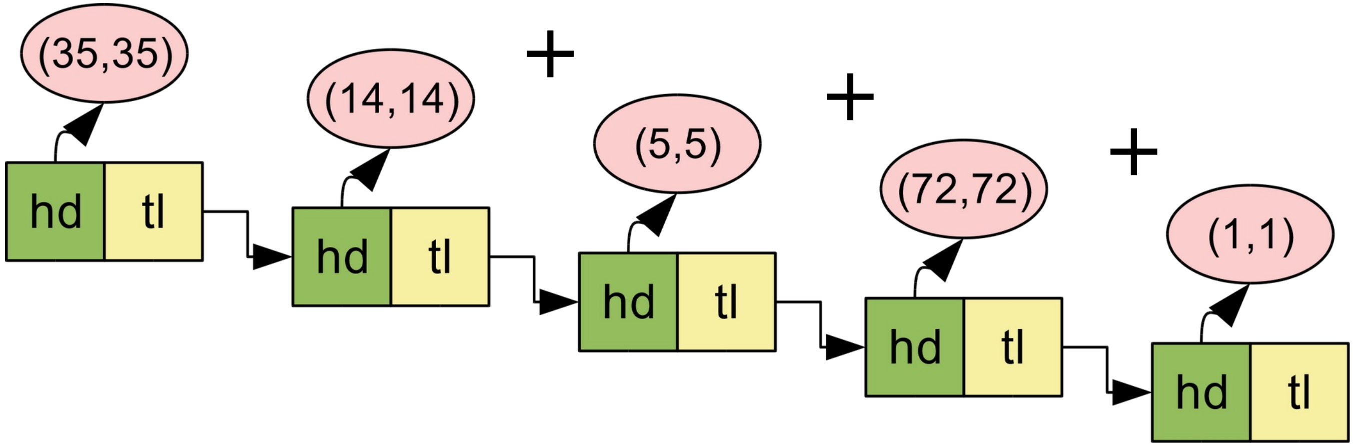


- If your pattern repeats, store and replay it for prefetching!
- Recently become viable in hardware: see the Arm Cache Miss Chaining (CMC) Prefetcher https://hc33.hotchips.org/assets/program/conference/day1/20210818_Hotchips_NeoverseN2.pdf

…but actually, linked lists aren’t as bad as you’d expect



```
let rec fold_left f accu l =
  match l with
    [] -> accu
  | a::l -> fold left f (f accu a) l;;
```



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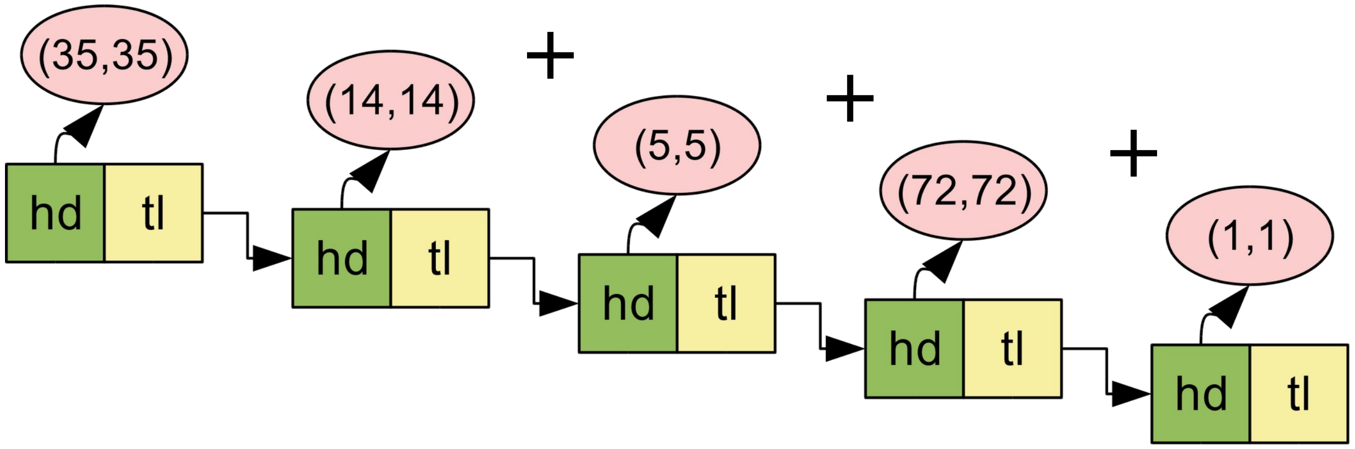
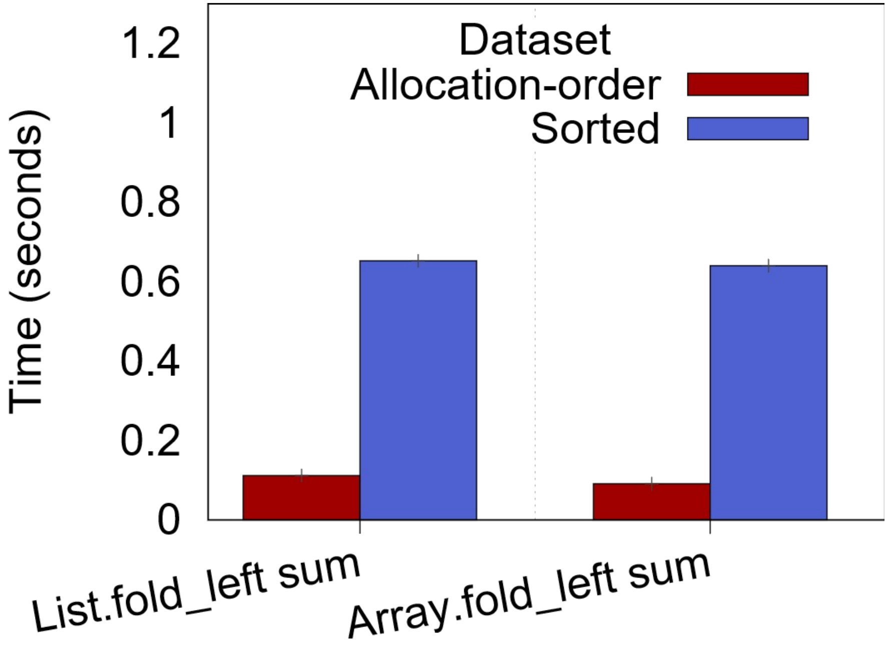
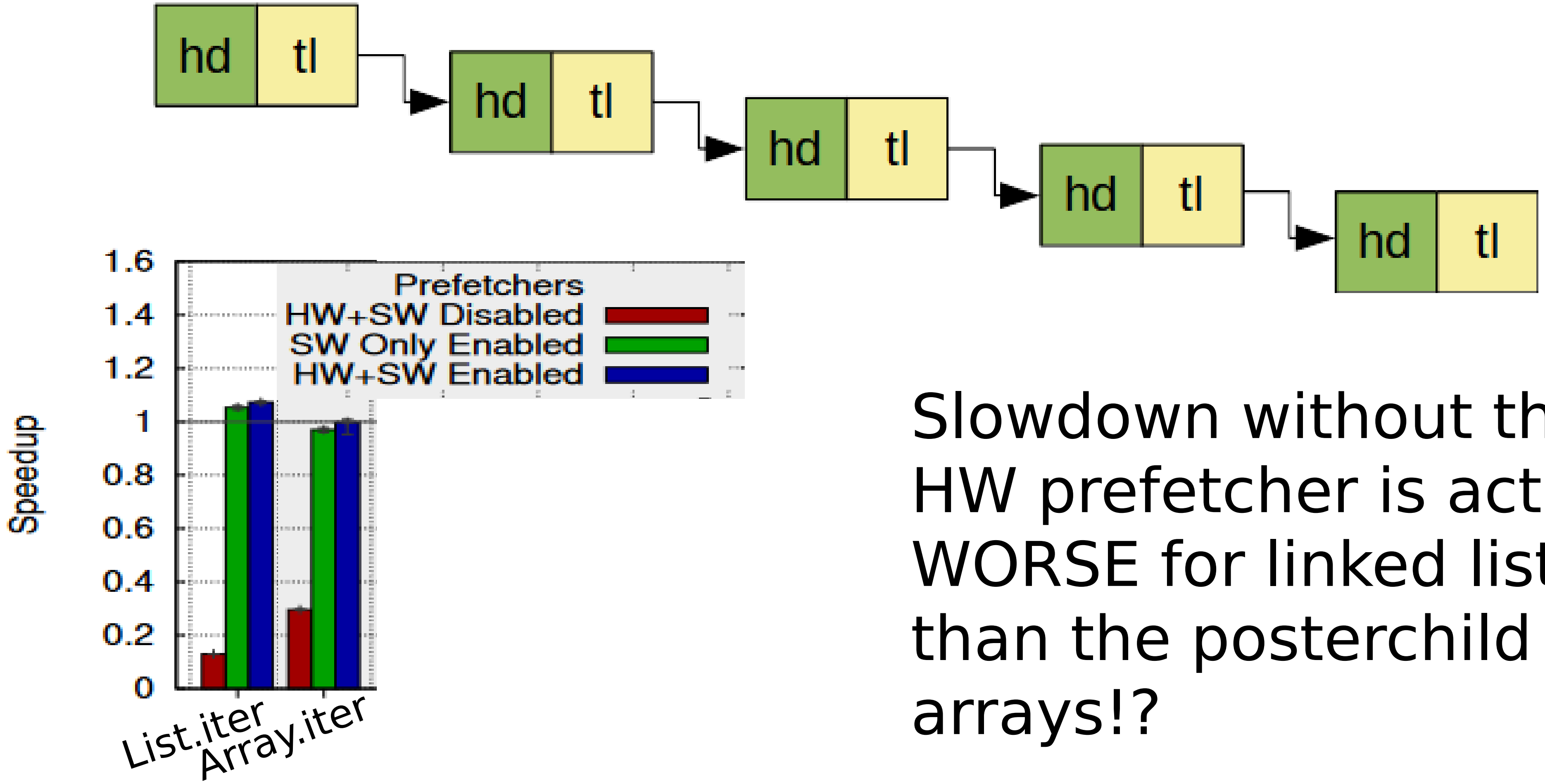


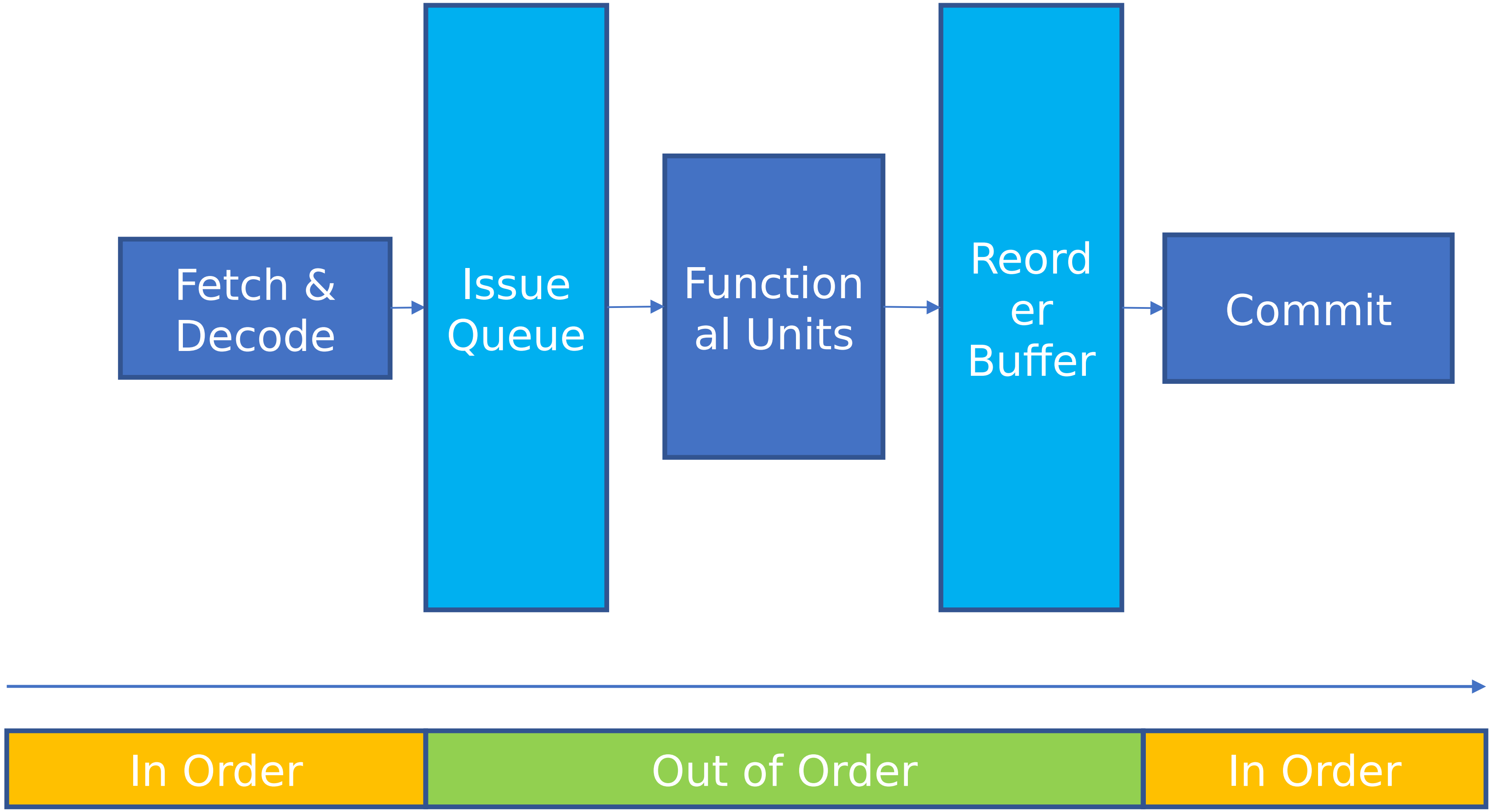


Our next clue: List.iter on unboxed integers with/without hardware prefetcher

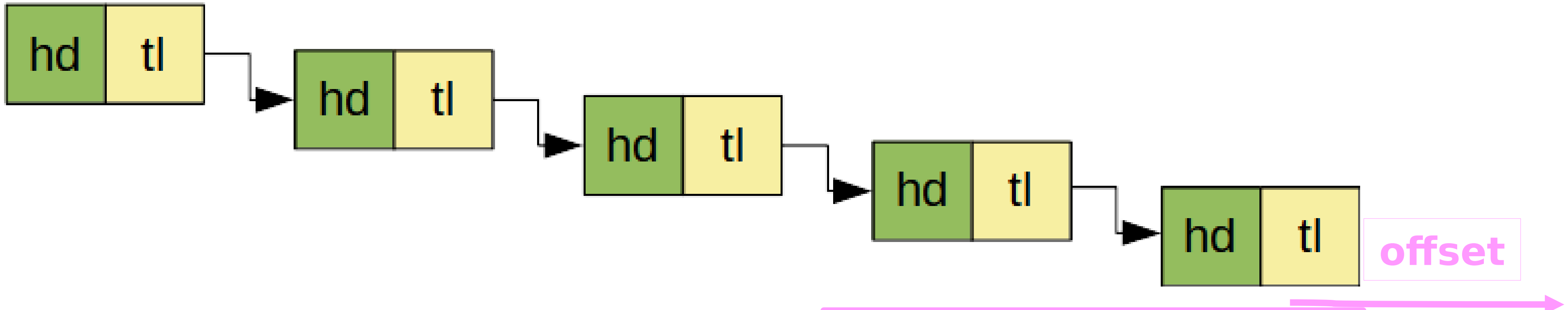


Slowdown without the HW prefetcher is actually WORSE for linked lists than the posterchild arrays!?

Out-Of-Order Execution



Idea: Jump off the deep end



```
prefetchoffset l (-256);
```

Idea: Jump off the deep end

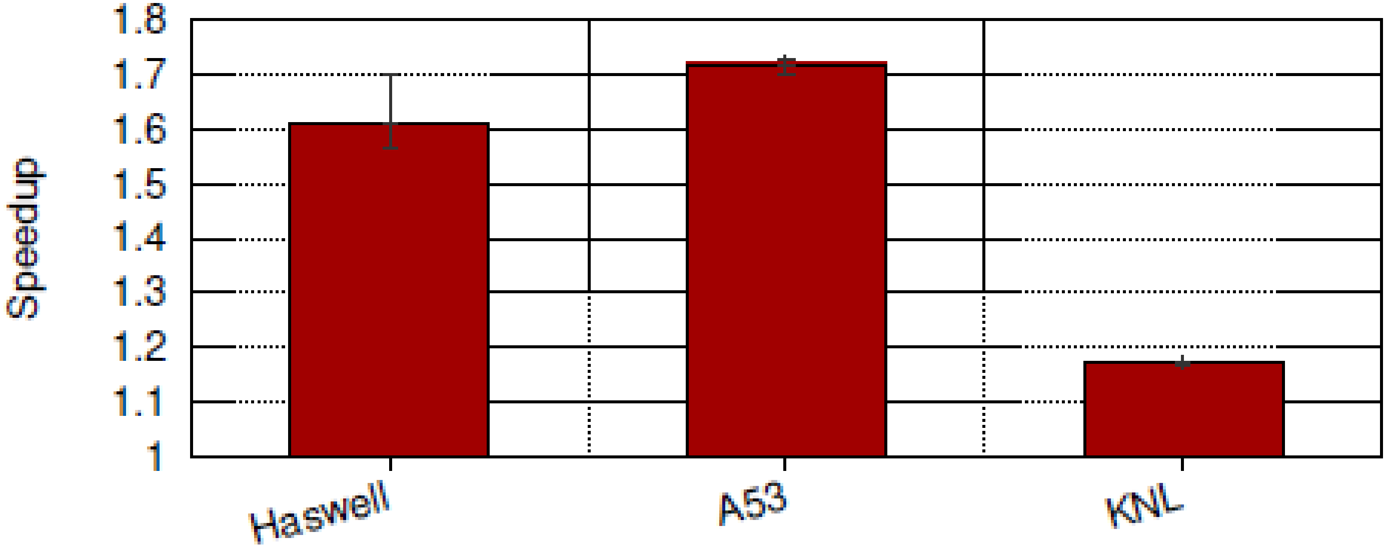
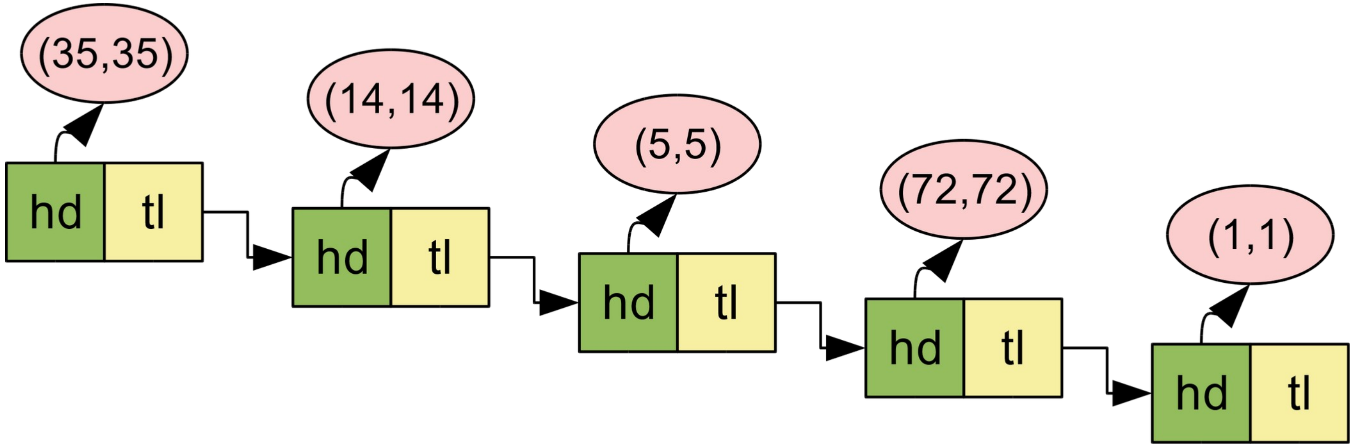
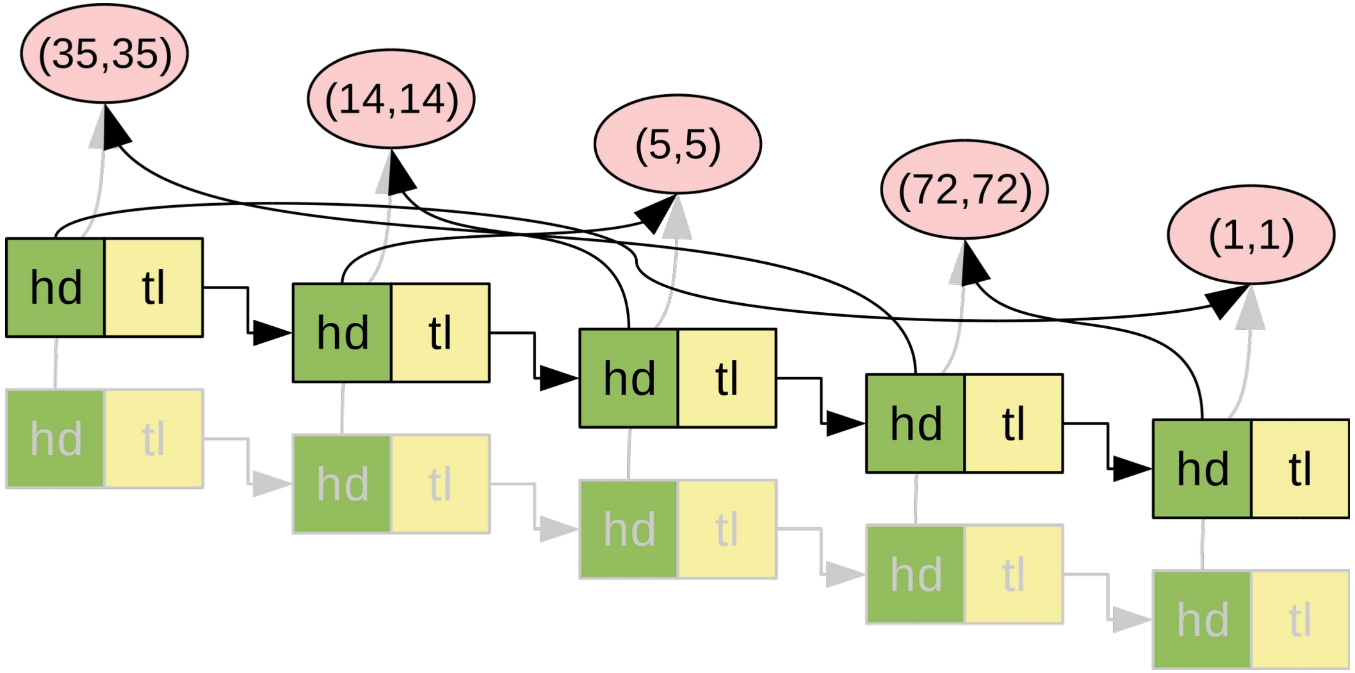


Figure 9. Speedup for prefetching *List.nth* on each system. Performance improvement remains consistent regardless of the linked list type, as the linked list data is not accessed.

Unsorted Lists



Sorted Lists



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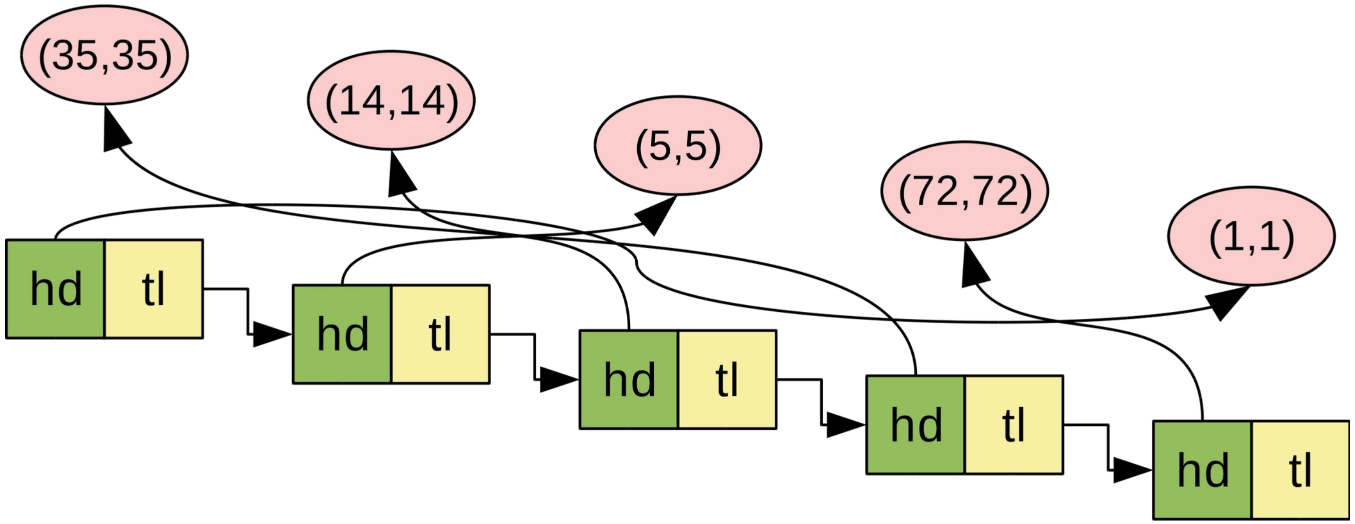
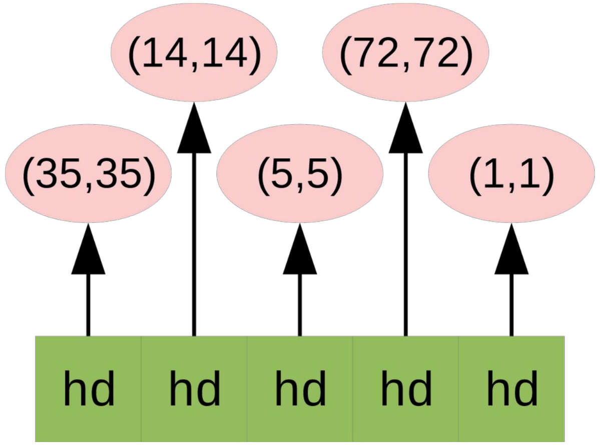
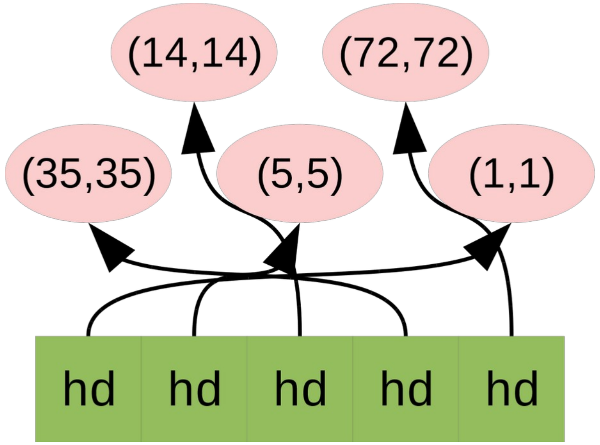


Unsorted Arrays

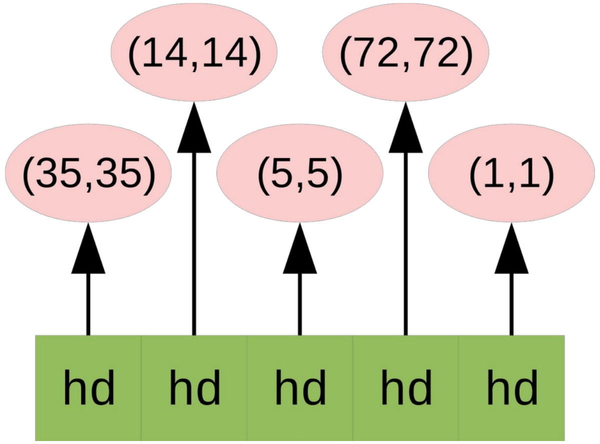


Sorted Arrays



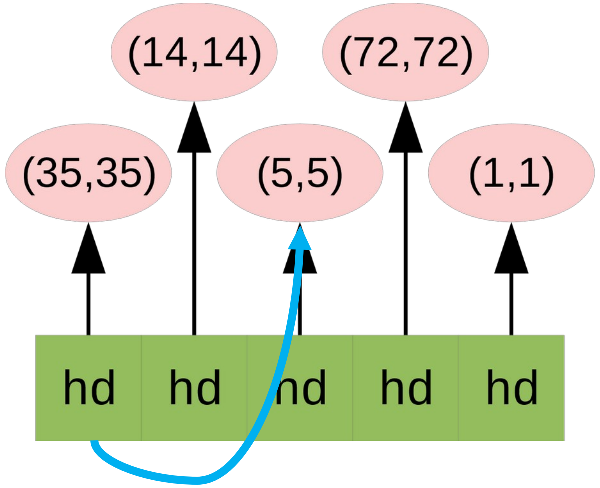
Array Prefetching

```
let fold_left_array f x a =
  let r = ref x in
  for i = 0 to length a - 1 do
    r := f !r (Array.unsafe_get a i)
  done;
  !r;;
```



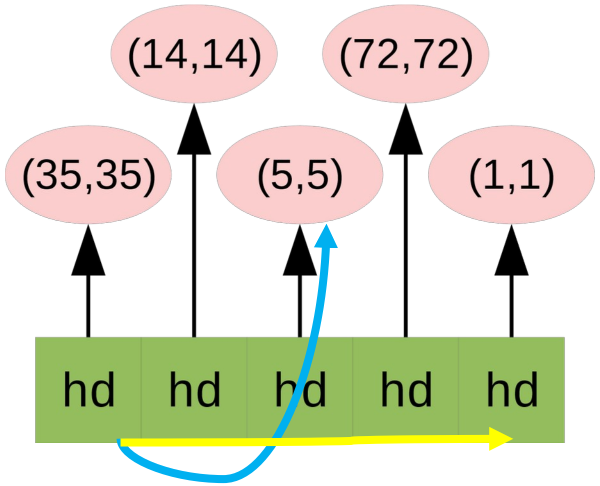
Array Prefetching

```
let fold_left_array f x a =
  let r = ref x in
  for i = 0 to length a - 1 do
    prefetch(Array.unsafe_get a (min (i+16)
    ((length a) - 1) ) );
    r := f !r (Array.unsafe_get a i)
  done;
  !r;;
```

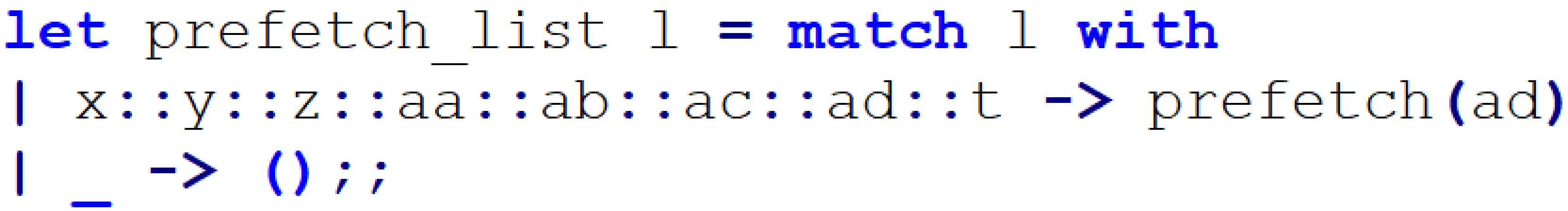


Array Prefetching

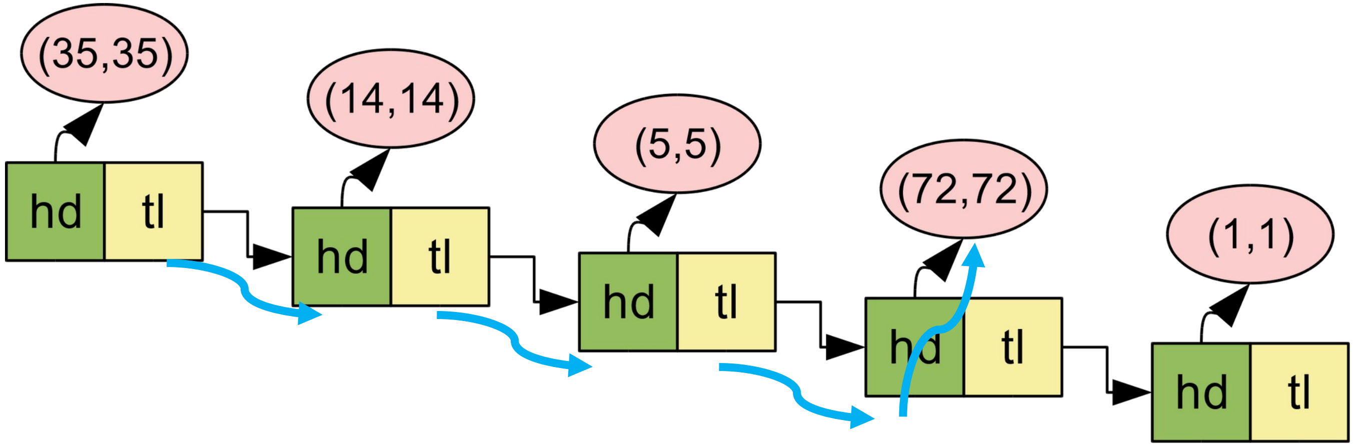
```
let fold_left_array f x a =
  let r = ref x in
  for i = 0 to length a - 1 do
    Array.array_prefetch a (i+32);
    prefetch(Array.unsafe_get a (min (i+16)
    ((length a) - 1) ) );
    r := f !r (Array.unsafe_get a i)
      ;
  !r;;
```



List Simple Prefetching



```
let prefetch_list l = match l with
| x::y::z::aa::ab::ac::ad::t -> prefetch(ad)
| _ -> ();;
```



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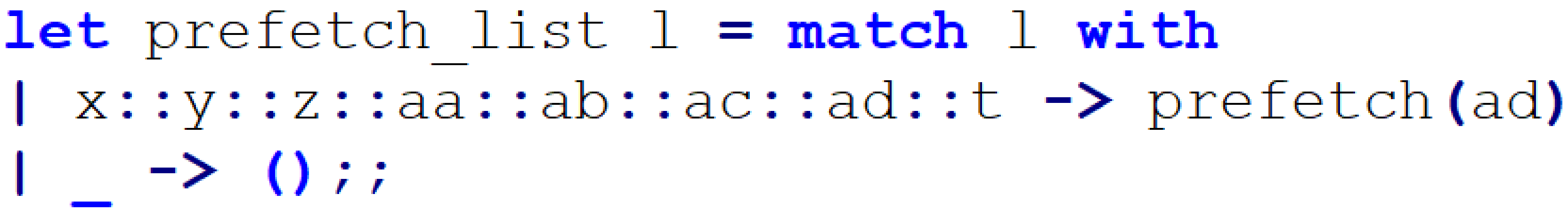

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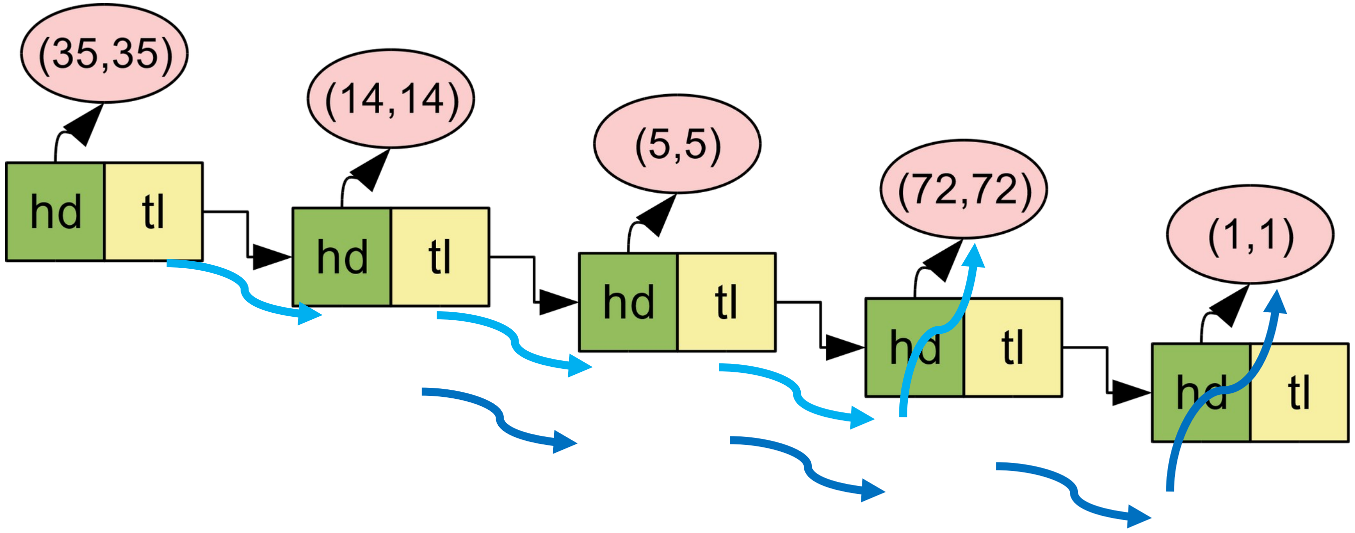
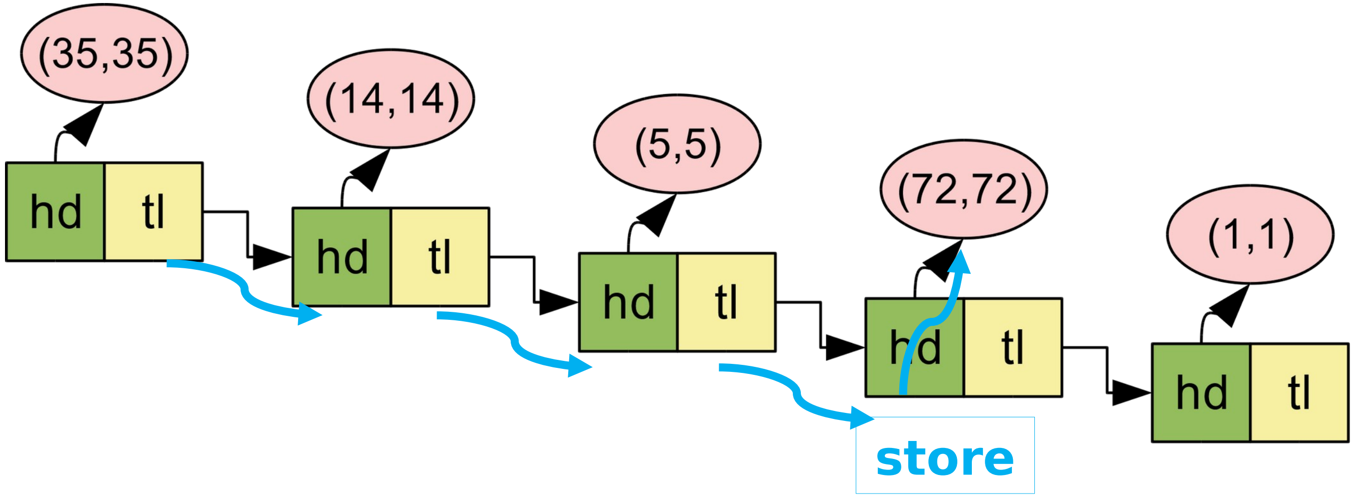


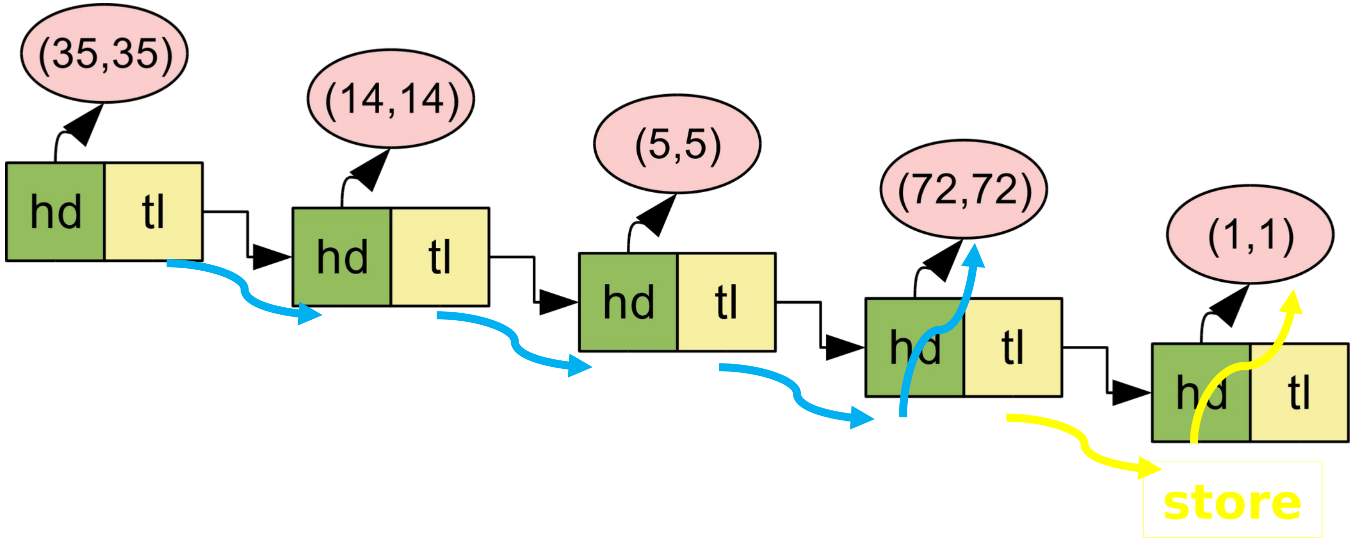
List Complex Prefetching

```
let prefetch_prefind l = match l with
|cx::cy::cz::caa::cab::cac::cae::cbad::cbx::cby::cbz::cbaa::cbab::cbac::cbae::cad::x
::y::z::aa::ab::ac::ae::bad::bx::by::bz::baa::bab::bac::bae::ad::t -> prefetch(ad); t
| _ -> [];;
```



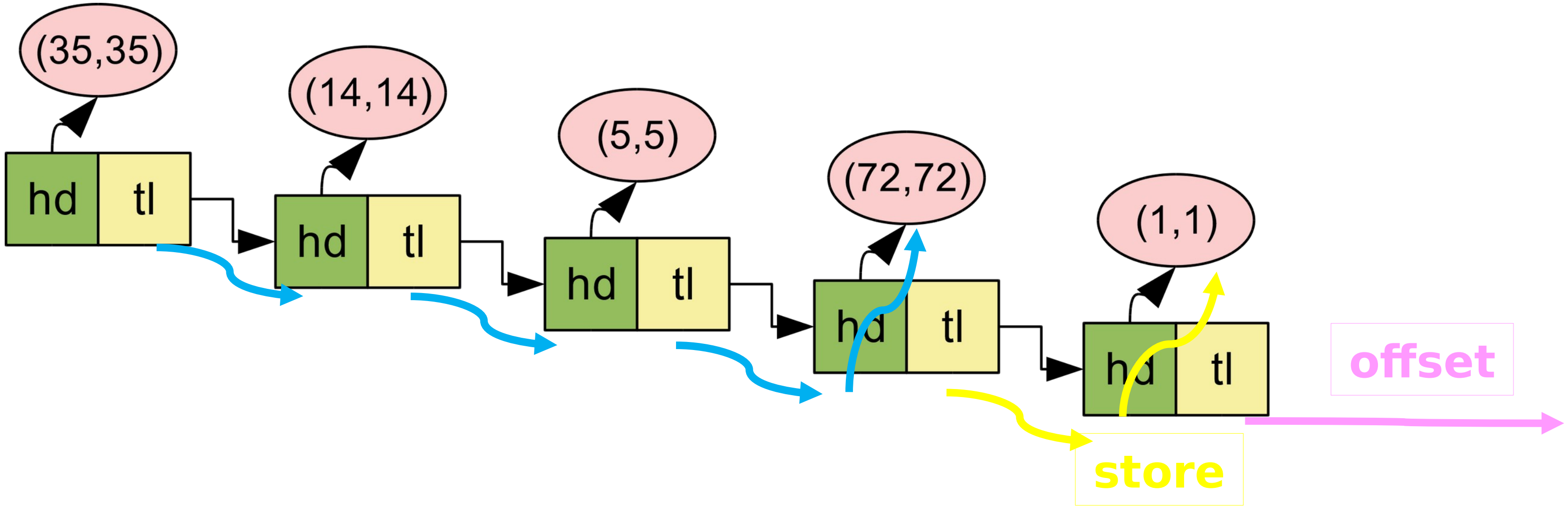
List Complex Prefetching

```
let prefetch_prefind l = match l with
|cx::cy::cz::caa::cab::cac::cae::cbad::cbx::cby::cbz::cbaa::cbab::cbac::cbae::cad::x
::y::z::aa::ab::ac::ae::bad::bx::by::bz::baa::bab::bac::bae::ad::t -> prefetch(ad); t
| _ -> [];;

let prefetch_prefound m = match m with
| x::ys -> prefetch(x);ys
| _ -> [];;
```



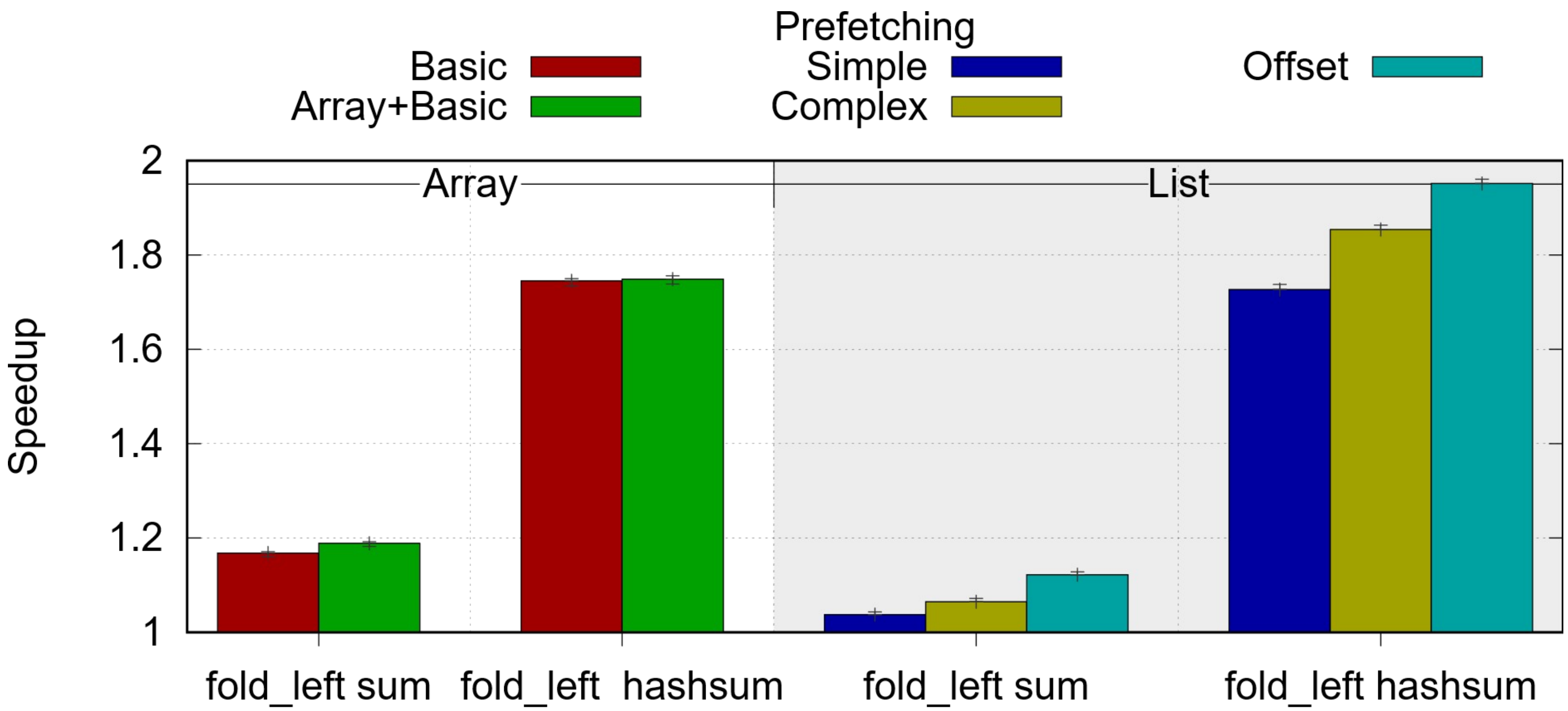
List Complex + Offset Prefetching

```
let prefetch_prefind l = match l with
|cx::cy::cz::caa::cab::cac::cae::cbad::cbx::cby::cbz::cbaa::cbab::cbac::cbae::cad::x
::y::z::aa::ab::ac::ae::bad::bx::by::bz::baa::bab::bac::bae::ad::t -> prefetch(ad); t
| _ -> [];;

let prefetch_prefound m = match m with
| x::ys -> prefetch(x);ys
| _ -> [];;
```

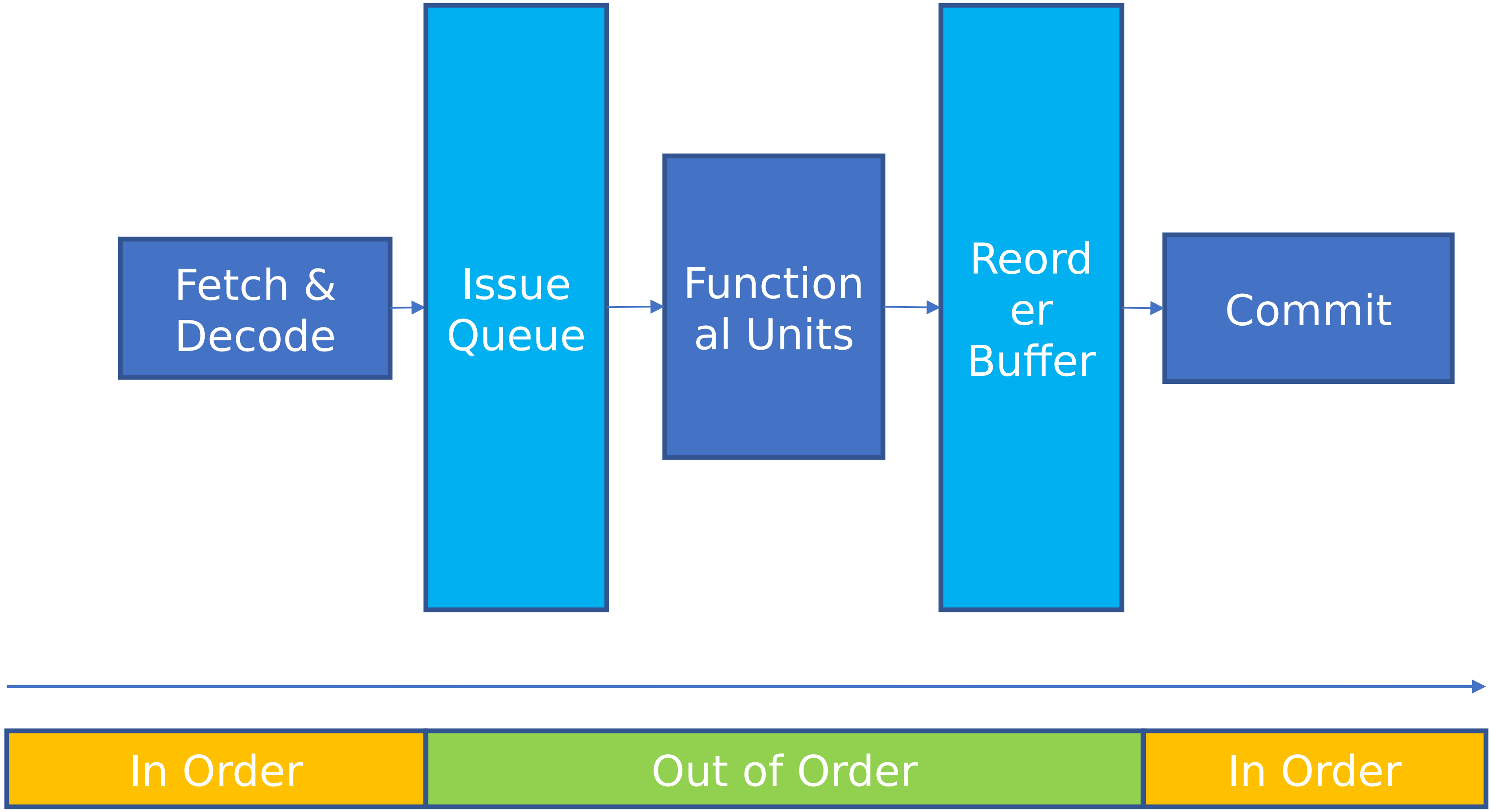


```
prefetchoffset l (-256);
```

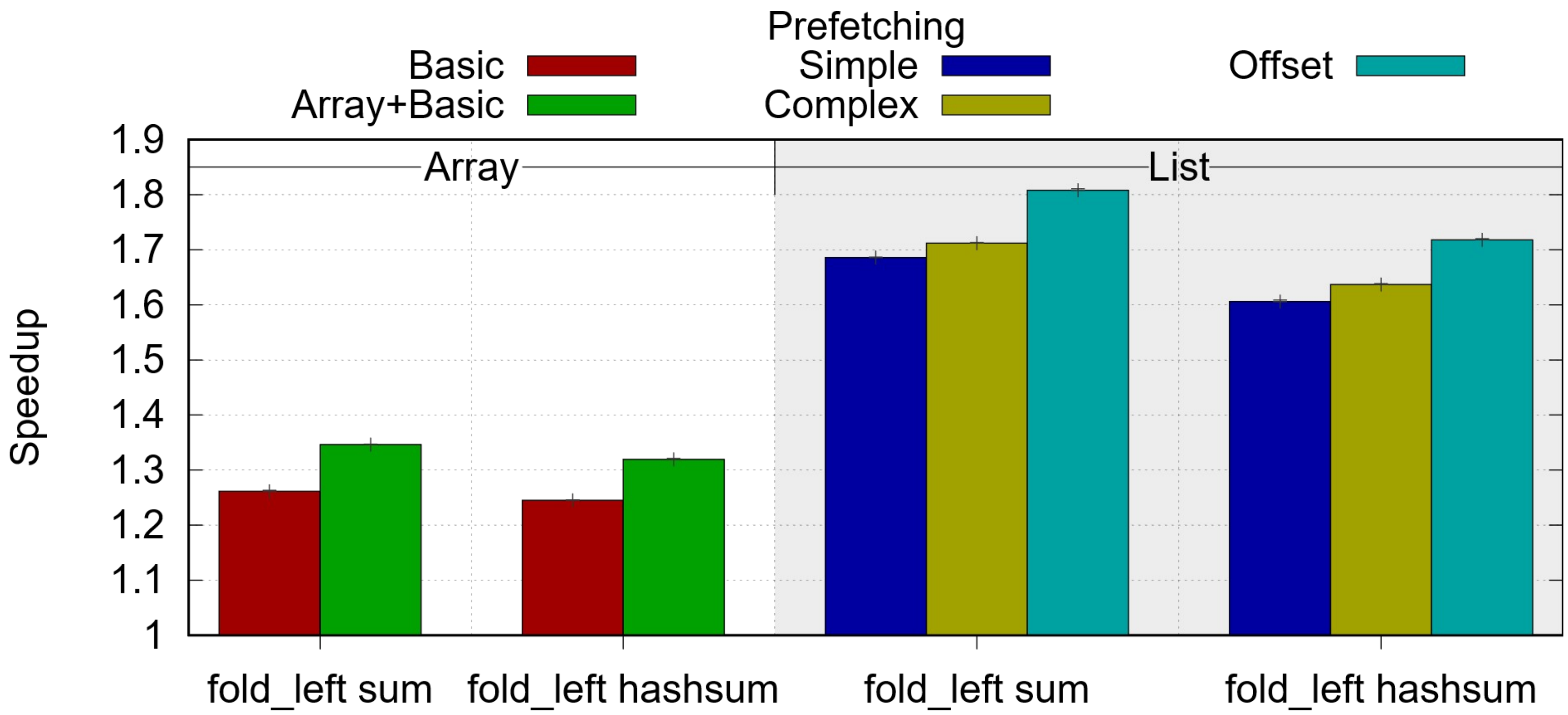
Fold_Left (Intel Haswell)



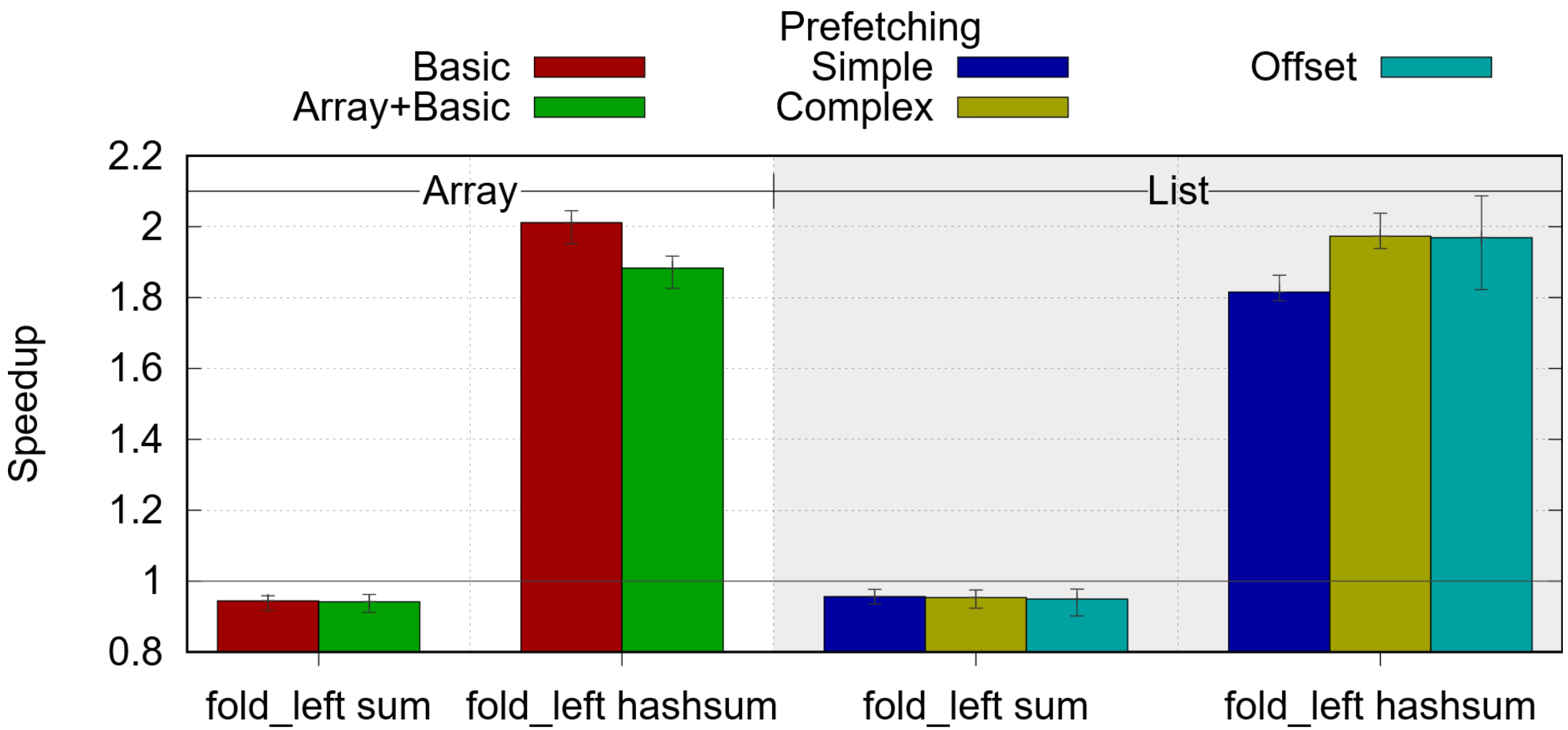
Out-Of-Order Execution



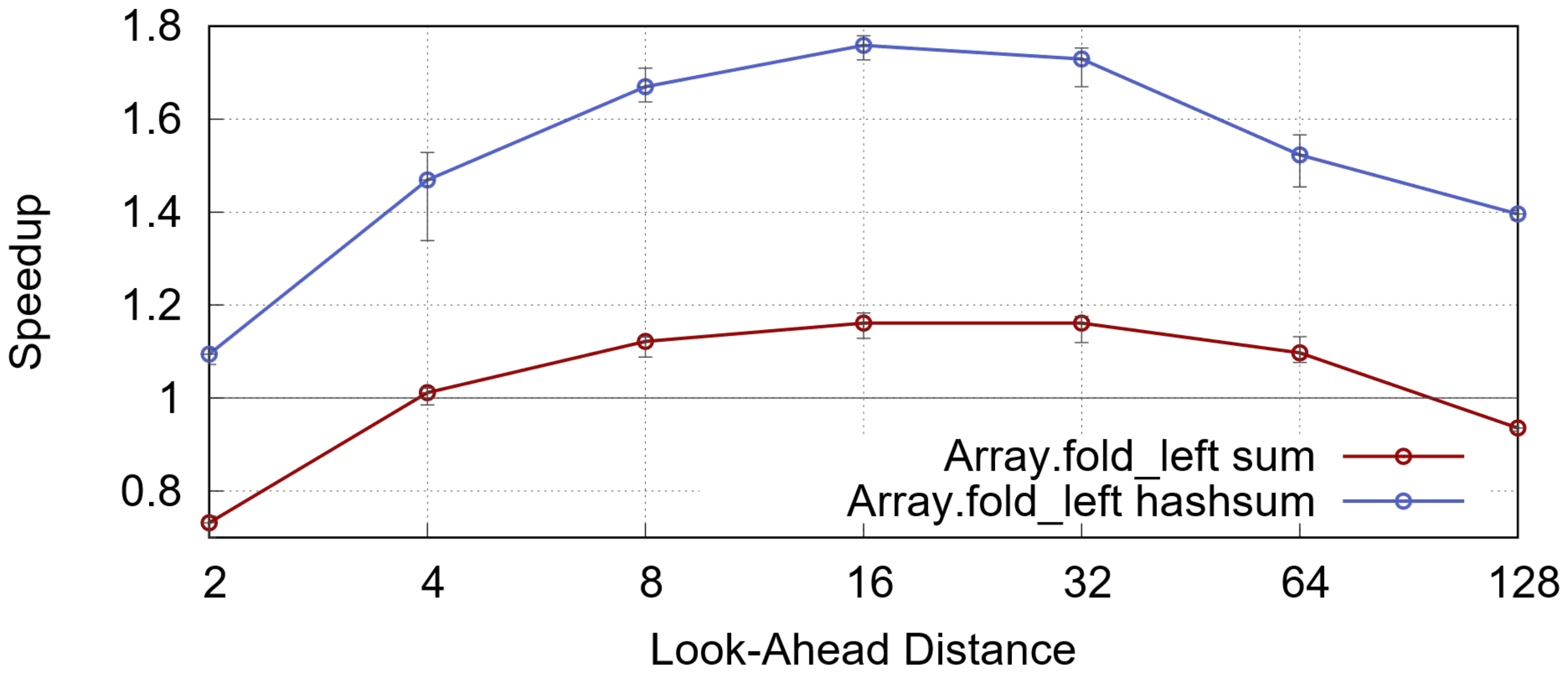
Fold_Left (Arm Cortex A53)



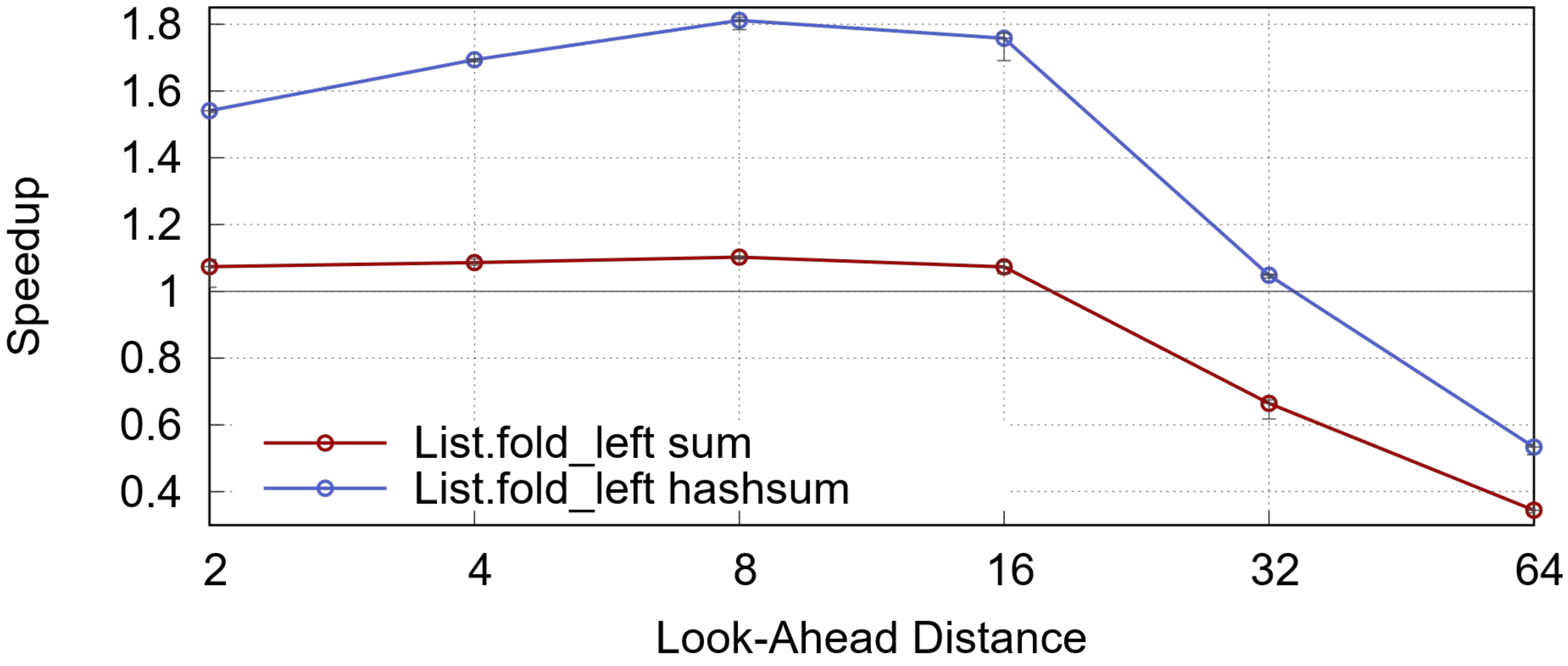
Fold_Left (Intel Xeon Phi Knights Landing)



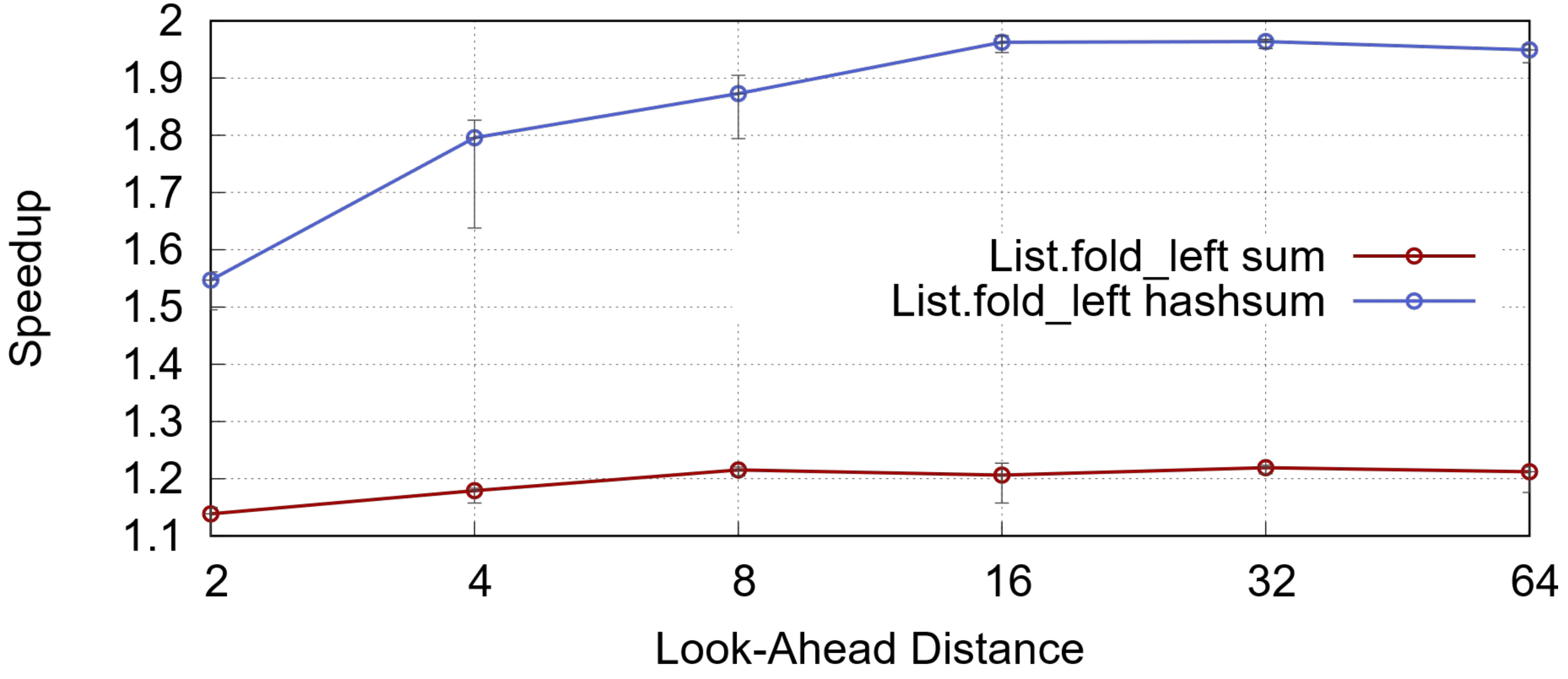
Fetch Distances (Arrays)



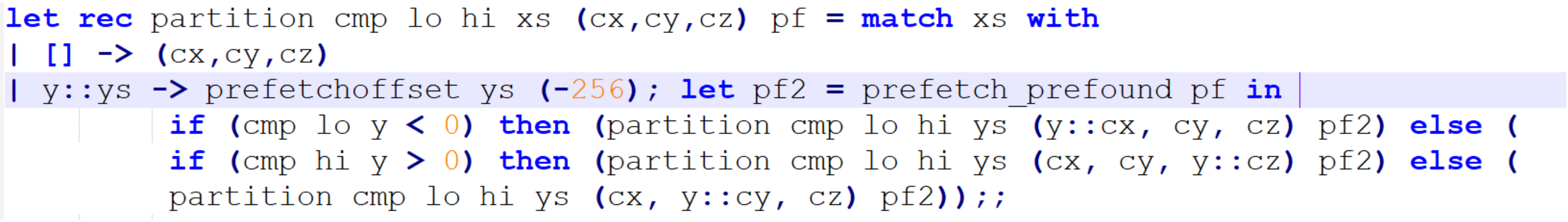
Fetch Distances (List Simple)



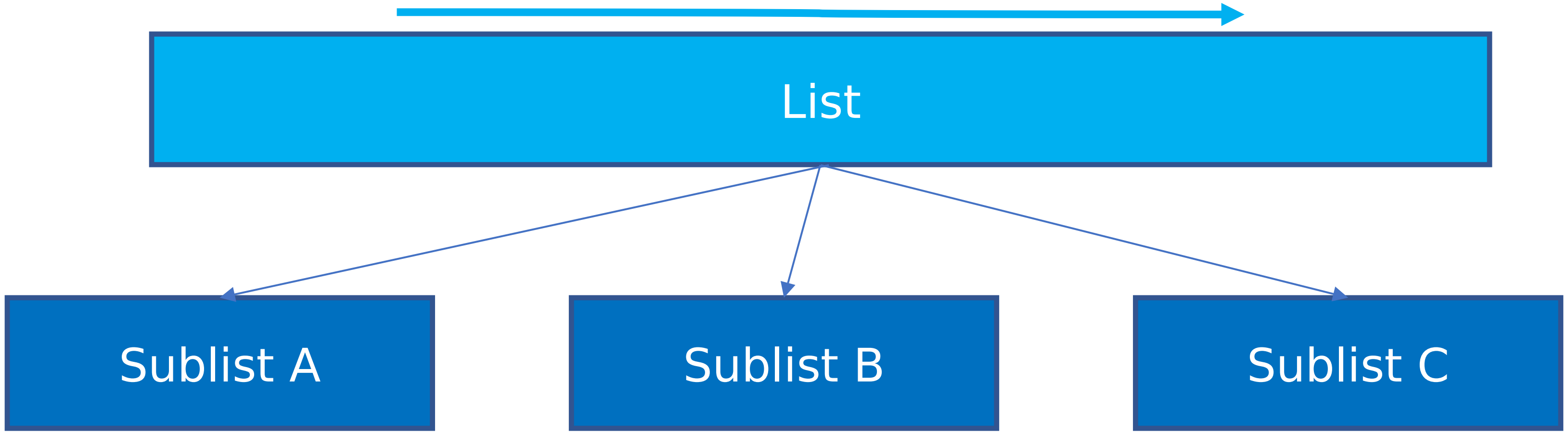
Fetch Distances (List Complex)



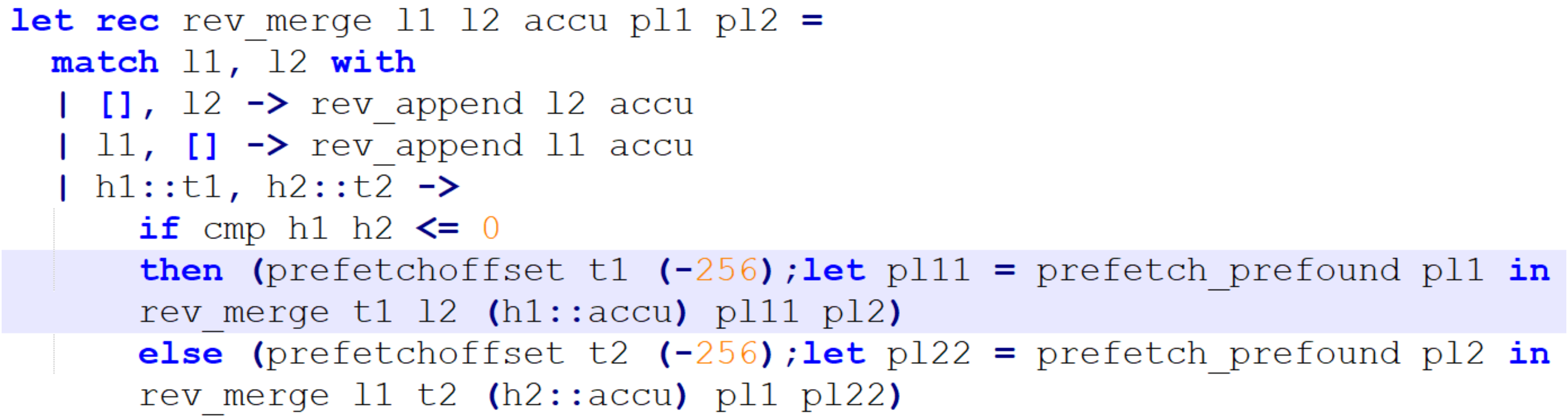
Quicksort



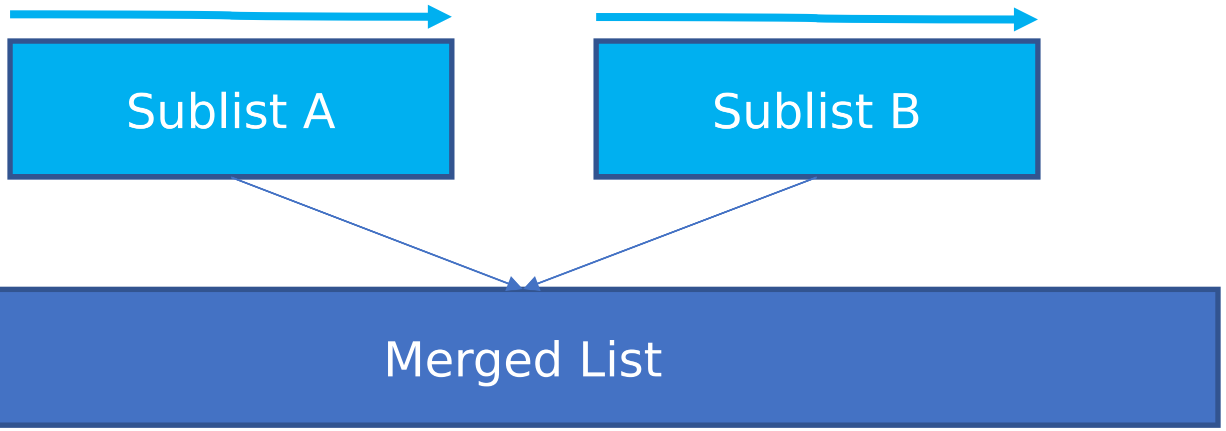
```
let rec partition cmp lo hi xs (cx,cy,cz) pf = match xs with
| [] -> (cx,cy,cz)
| y::ys -> prefetchoffset ys (-256); let pf2 = prefetch_prefound pf in
         if (cmp lo y < 0) then (partition cmp lo hi ys (y::cx, cy, cz) pf2) else (
         if (cmp hi y > 0) then (partition cmp lo hi ys (cx, cy, y::cz) pf2) else (
         partition cmp lo hi ys (cx, y::cy, cz) pf2));;
```



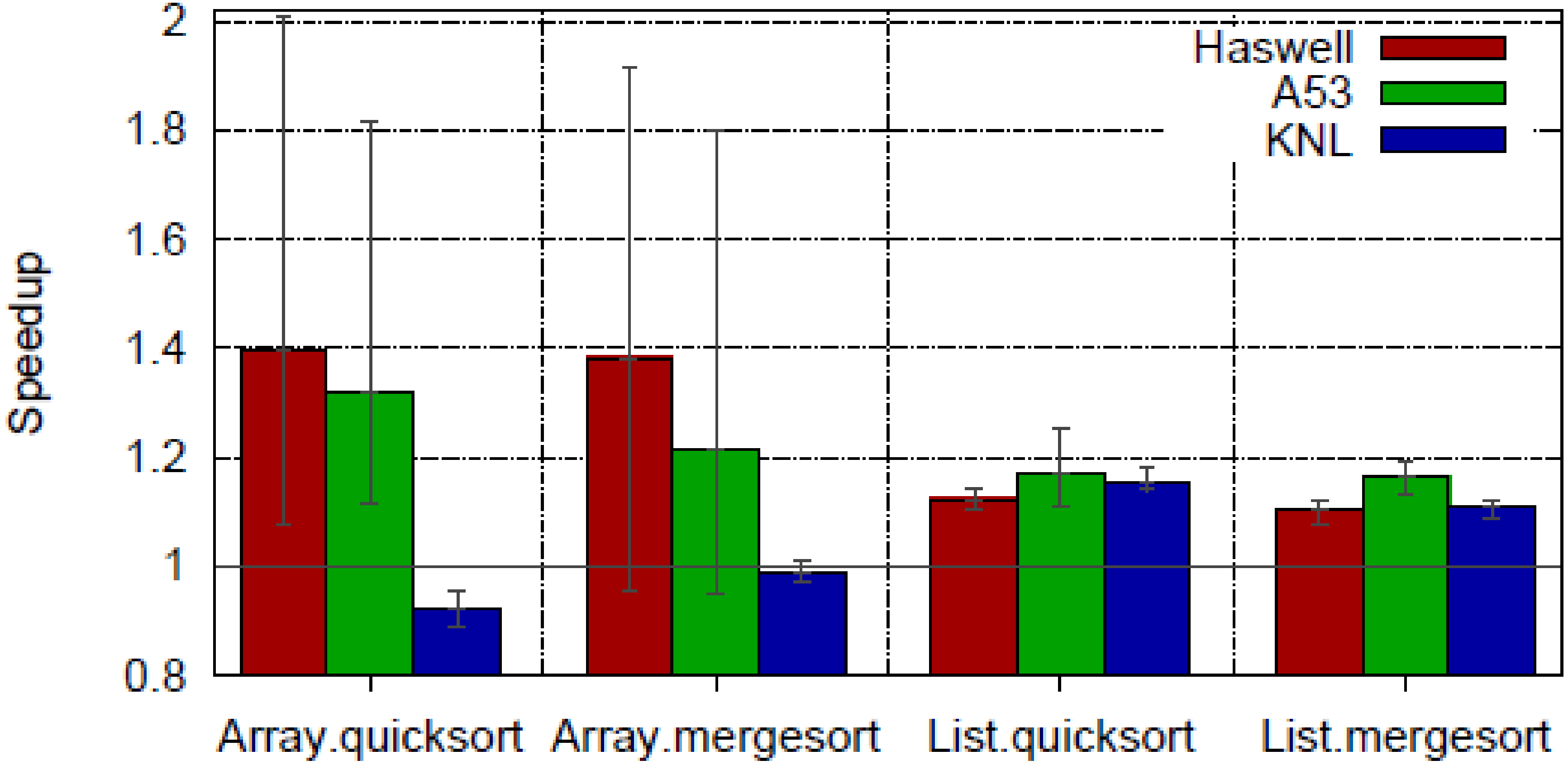
Mergesort



```
let rec rev_merge l1 l2 accu pl1 pl2 =
  match l1, l2 with
  | [], l2 -> rev_append l2 accu
  | l1, [] -> rev_append l1 accu
  | h1::t1, h2::t2 ->
      if cmp h1 h2 <= 0
      then (prefetchoffset t1 (-256);let pl11 = prefetch_prefound pl1 in
      rev_merge t1 l2 (h1::accu) pl11 pl2)
      else (prefetchoffset t2 (-256);let pl22 = prefetch_prefound pl2 in
      rev_merge l1 t2 (h2::accu) pl1 pl22)
```



See it, Say it, Sorted

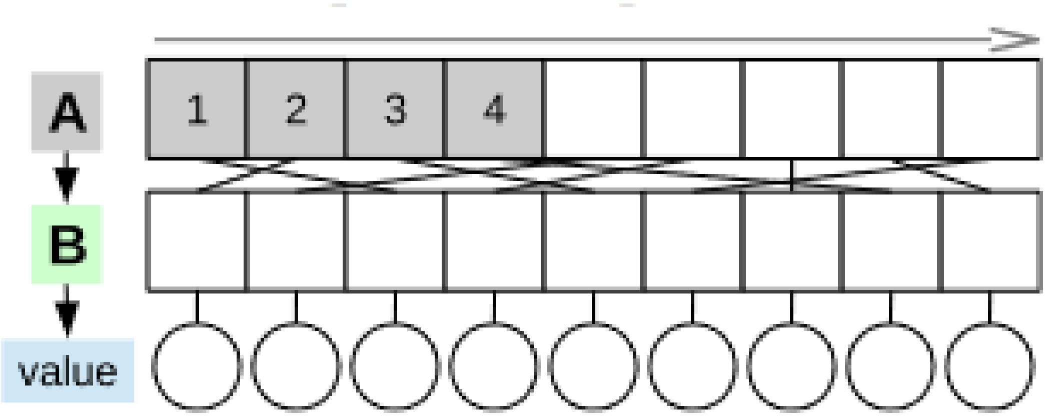


What does this all mean for microarchitecture and compilers on functional languages?

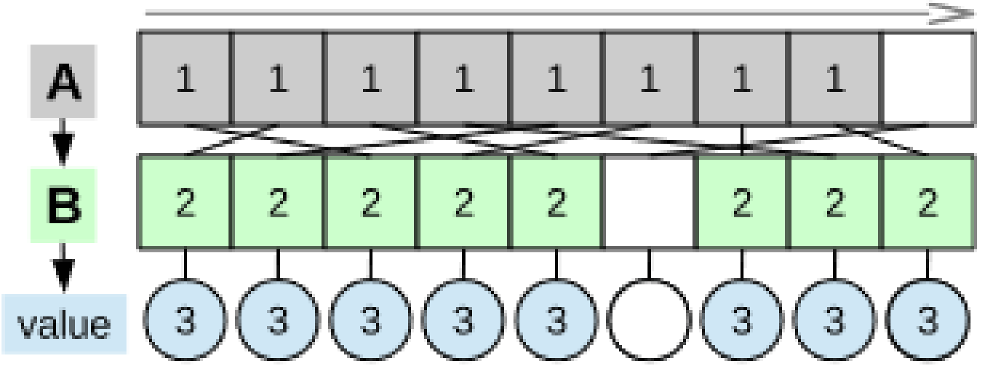
- Out-of-order cores are bad at linked data structures – too many data dependencies
- Hardware prefetchers are good at linked lists – they can value-predict past the data dependencies if the allocator does its job
- Software prefetching can do much better, both in terms of aggression, and following new patterns… and it has no (hard) state so kind-of suitable for functional langs
- BUT – the correct software prefetch depends not only on the code, but the dataset distribution and size (so run-time information…)

Another thought: Vector Runahead
(ISCA 2021, MICRO 2023, Top Picks 2022 and 2024)

```
for (int x=0; x<N; x++)
y += B[hash(A[x])]->value;
```



Stride prefetcher



Vector Runahead: learns from the stride prefetcher, spawns new gather code in vectors

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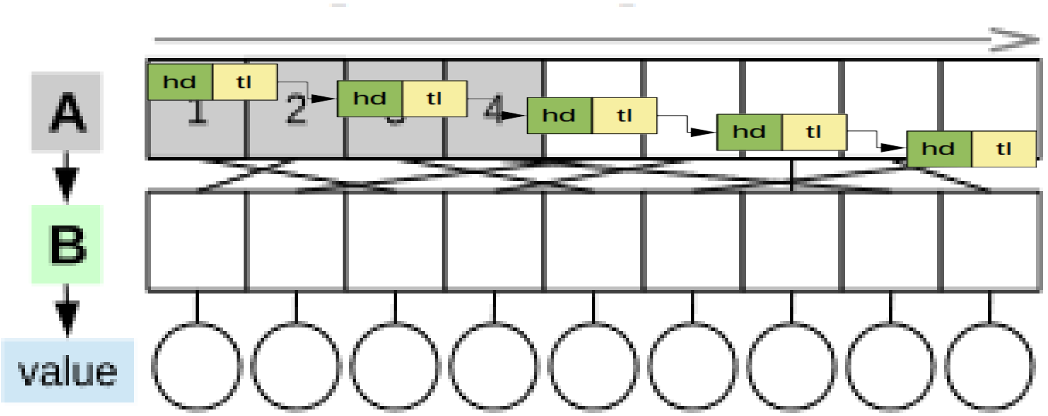
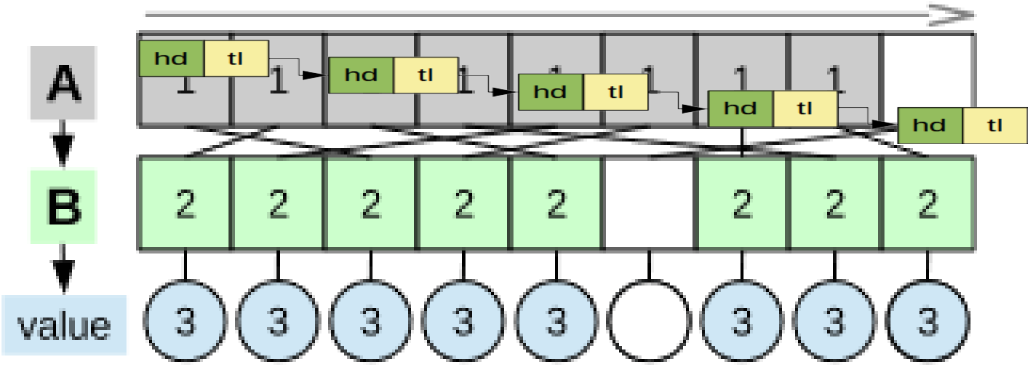


Stride prefetcher



Vector Runahead: learns from the stride prefetcher, spawns new gather code in vectors

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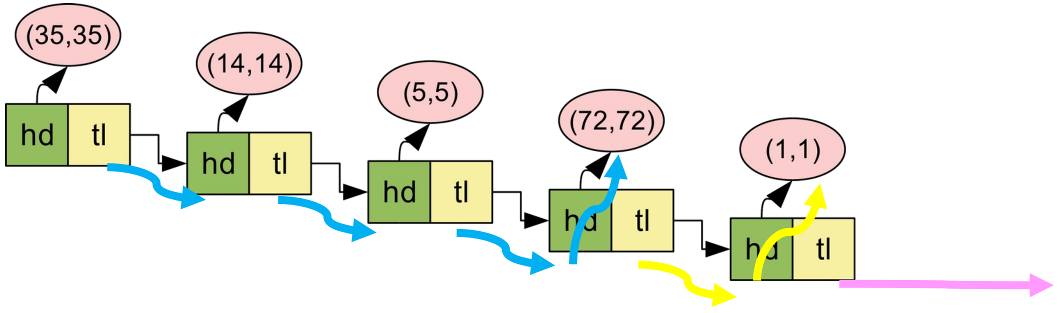
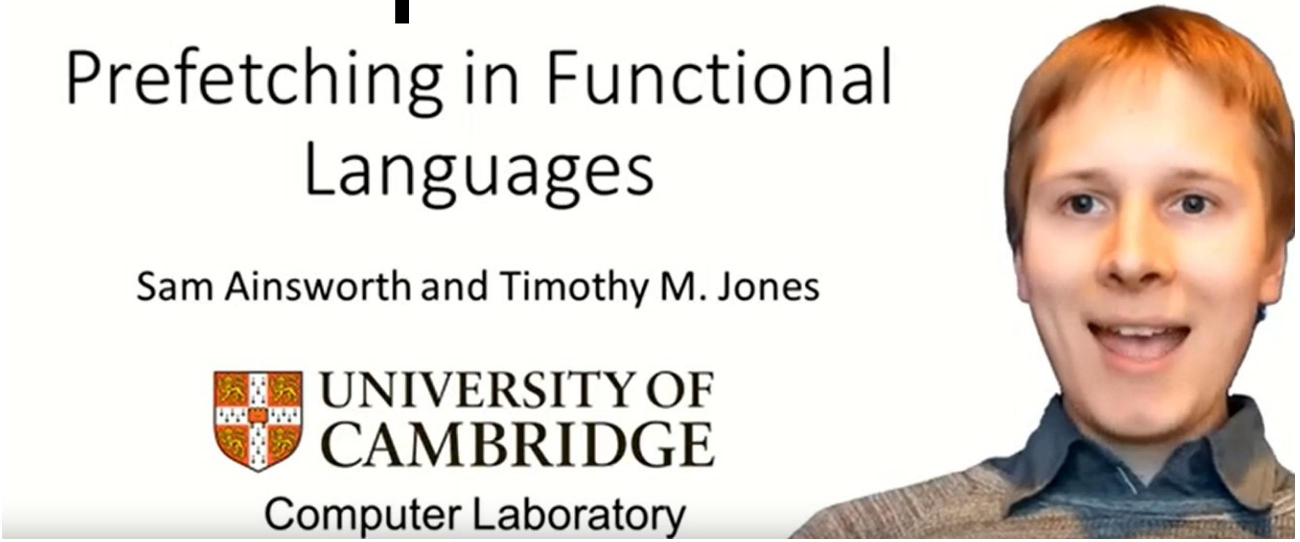




Prefetching in Functional Languages

Sam Ainsworth and Timothy M. Jones

UNIVERSITY OF CAMBRIDGE

Computer Laboratory

Watch the ISMM Talk!

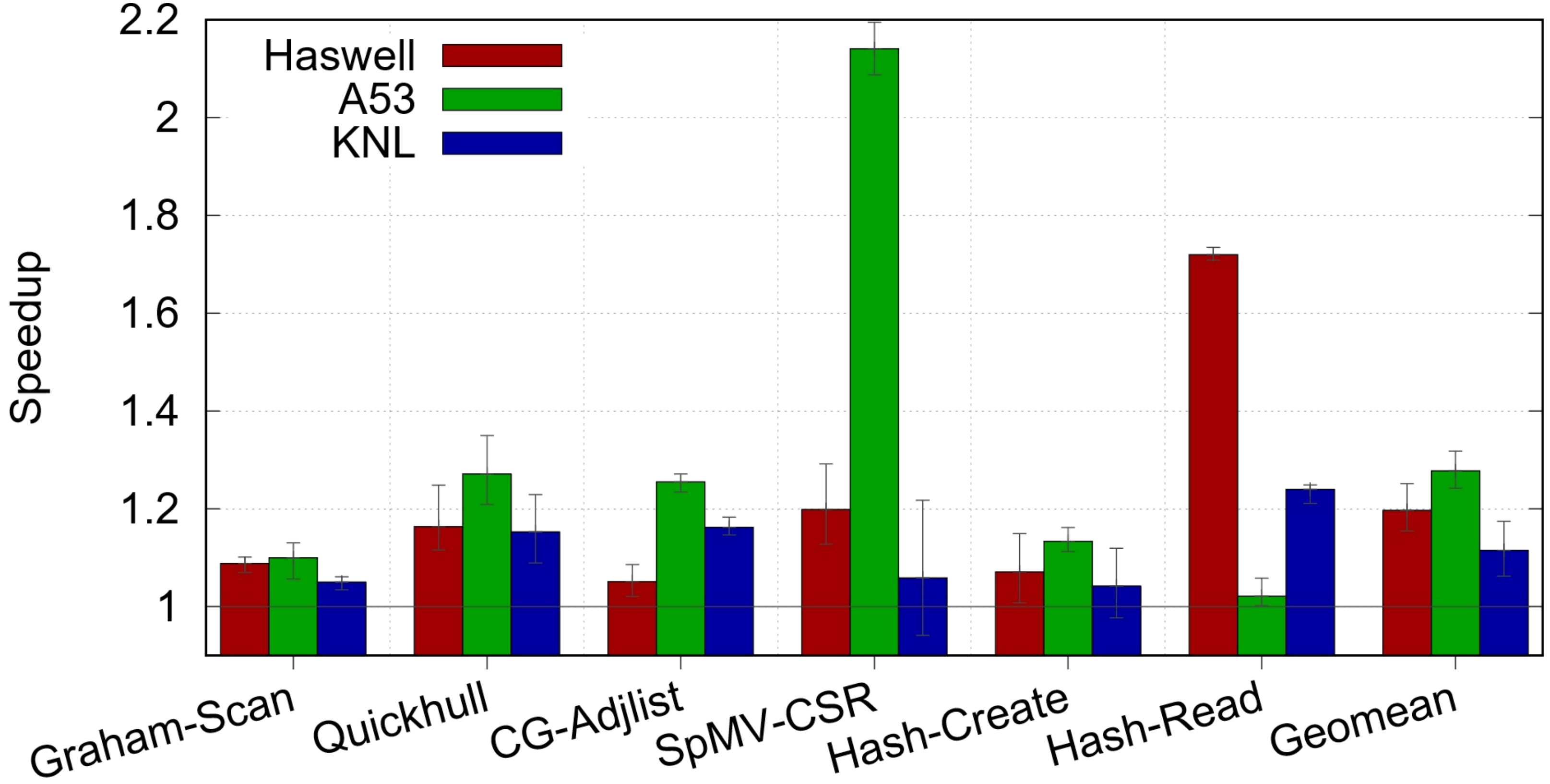
https://www.youtube.com/watch?v=5fTt1I1ePCg

Sam Ainsworth

OCaml memory-bound benchmark suite

Workload	Prefetching	Description
Graham Scan	List Complex, Offset (via sorting algorithm)	Calculates the convex hull of a list of integer pairs, by sorting the points then categorizing them.
Quickhull	List Complex, Offset	Calculates the convex hull of a list of integer pairs, using a quicksort-style divide-and-conquer approach.
CG-Adjlist	Array, Basic, Offset	Conjugate-gradient solving for graphs in adjacency-list format.
SpMV-CSR	Array, Basic	Performs sparse matrix-vector multiplication on graphs based on an efficient compressed sparse-row (CSR) representation.
Hash-Create	Array	Times the creation and filling of a large hash table.
Hash-Read	Array, Basic	Times reading all the elements of a large hash table.

OCaml memory-bound benchmark suite


Speedup
Haswell
A53
KNL
Graham-Scan
Quickhull
CG-Adjlist
SpMV-CSR
Hash-Create
Hash-Read
Geomean