NumaMMA
NUMA MeMory Analyzer

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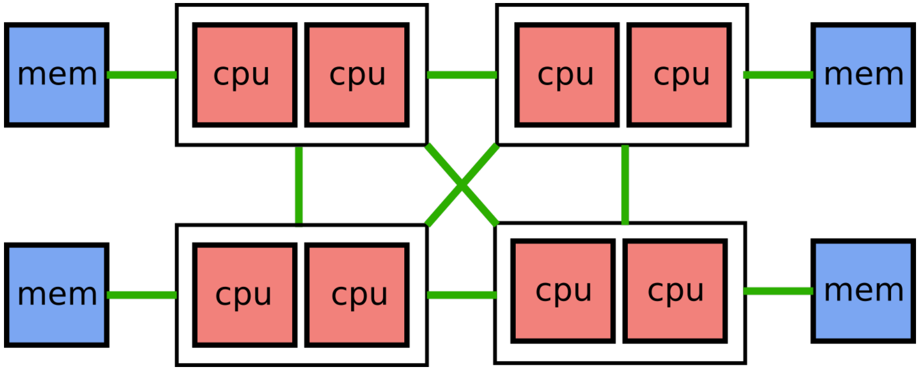
NUMA architecture

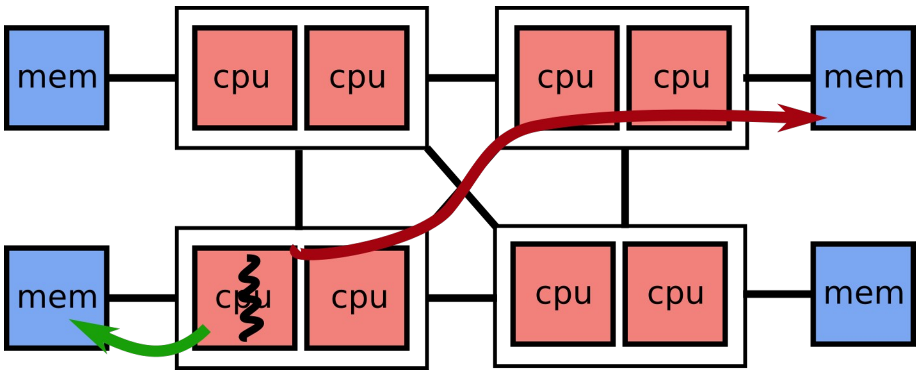
NUMA architectures are now common

- Multi-socket systems
- Multicore CPUs
  - AMD Infinity Fabric (Zen CPU family)
  - Intel sub-NUMA clustering (Skylake family)
- Increase the available memory bandwidth



Impact of locality

- **NUMA = Non Uniform Memory Access**
  - Fast access to the local memory
  - Slower access to remote NUMA nodes



→ **the locality of memory access impacts the performance**

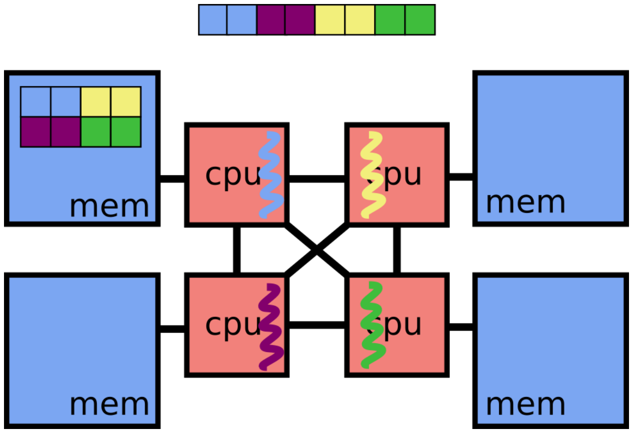
eg. impact on NPB LU on a 48-core machine: up to 27%

→ **need to allocate pages on the right NUMA node**

Memory allocation strategies
First-touch policy

- ***First-touch* policy**
  - Default policy on Linux
  - Lazy allocation policy
  - Allocate a page locally when a thread touches it
    - Assumption: this thread is probably the one that will use the page the most
      - Assumption may be wrong !

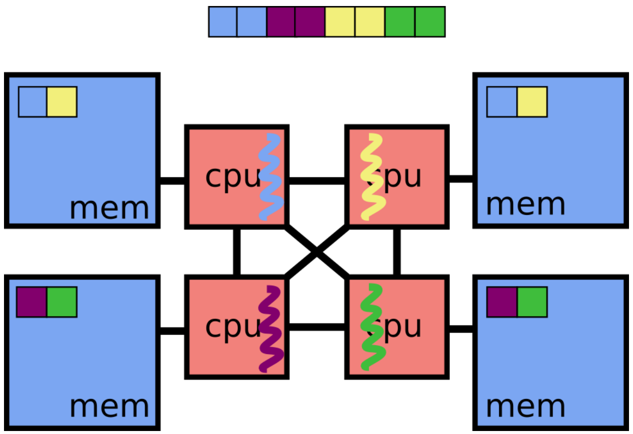
```
double *array = malloc(sizeof(double)*N);

for(int i=0; i<N; i++) {
  array[i] = something(i);
}

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```



Memory allocation strategies
Interleaved

- ***Interleaved* policy**
  - The pages are allocated on multiple nodes in round-robin
    → Balance the load on multiple NUMA nodes

```
double *array = numa_alloc_interleaved(sizeof(double)*N);

for(int i=0; i<N; i++) {
  array[i] = something(i);
}

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```



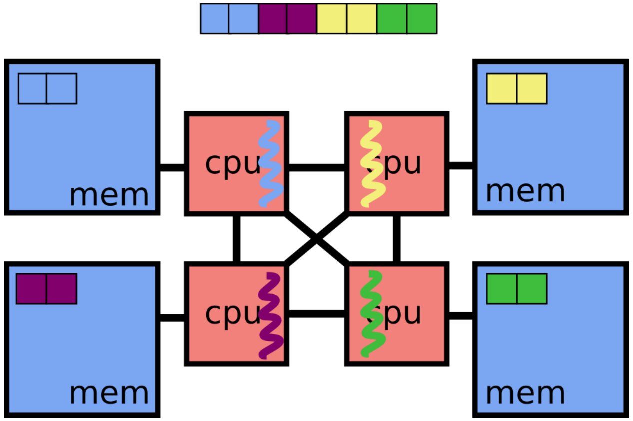
Manual placement of memory pages

- Move pages to a specific NUMA node with mbind() or move_pages()

  + precise control of page placement

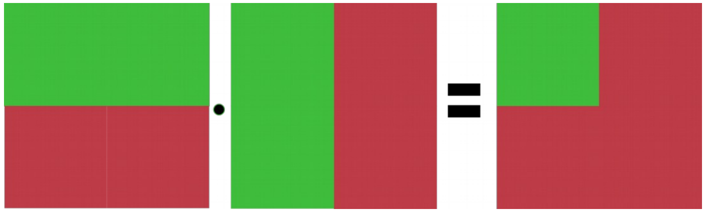
  - manual placement of each page

```
double *array = malloc(sizeof(double)*N);

for(int i=0; i<N; i++) {
  array[i] = something(i);
}

mbind(&array[0], N/4*sizeof(double),
      MPOL_BIND, &nodemask, maxnode,
      MPOL_MF_MOVE);

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```



Choosing the best binding policy

- **The threads access pattern may differ from one object to another**
  - eg. Matrix multiplication

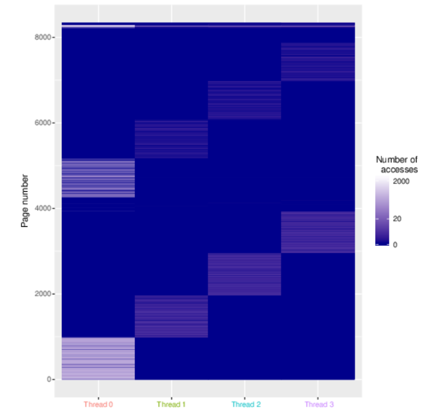


- **The best policy for one object may degrade the performance for another object**

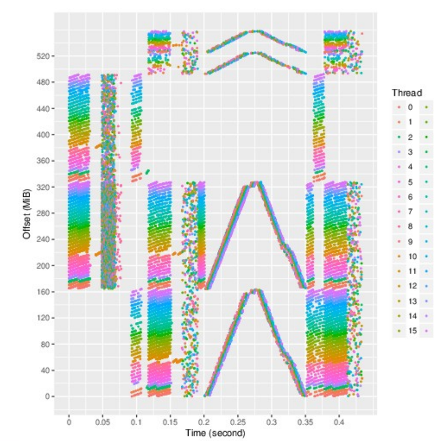
- **Is it worth finding the best policy for one object ?**
  - Some objects are rarely accessed

■ **NumaMMA – NUMA MeMory Analyzer**

- Analyze the memory access pattern of parallel applications
  - Low overhead collection of memory access



- Report:
  - The most accessed memory objects
  - Which thread access which part of an object
  - The evolution of access patterns over the time



- Freely available as open-source
  - https://github.com/numamma

NumaMMA
Collecting memory access information

Hardware memory sampling

- eg. Intel PEBS, AMD IBS
- Every X instructions, the CPU collects a sample
  - Address of the memory load/store
  - Thread/Instruction that issued the memory access
  - Where the data is stored (cache, RAM, remote RAM, …)
  - Cost of the memory access (ie. latency)
- Information stored in a buffer
- Low overhead sampling (eg. < 1-2 %)

```
#tid  timestamp     address        mem_level     latency
0     5835423725112 0x557735cf07c8 L2 Hit          24
0     5835456302591 0x557736353ef8 Local RAM Hit  779
0     5835466068752 0x55773642a0c0 Local RAM Hit  657
0     5835471131886 0x5577362726e8 L2 Hit          23
0     5835566865010 0x557735d1fd28 L3 Hit          52
0     5835567586835 0x557735d04710 L3 Hit          64
0     5835604540592 0x557736320900 Local RAM Hit 1585
0     5835605025940 0x557735c39900 Local RAM Hit  265
0     5835618194705 0x557735f0e428 L2 Hit          24
0     5835693753719 0x557735f16a78 L2 Hit          23
0     5835709318658 0x557736260f00 Local RAM Hit  266
```

NumaMMA
Identifying memory objects

- **Static memory object**
  - eg. global variables
  - Search for symbols in the ELF binary
- **Dynamic memory objects**
  - malloc, realloc, calloc, free, …
  - Intercept dynamic allocations with LD_PRELOAD
- **For each object, NumaMMA knows**
  - The allocation/de-allocation timestamp
  - The start/end address

NumaMMA
Matching samples

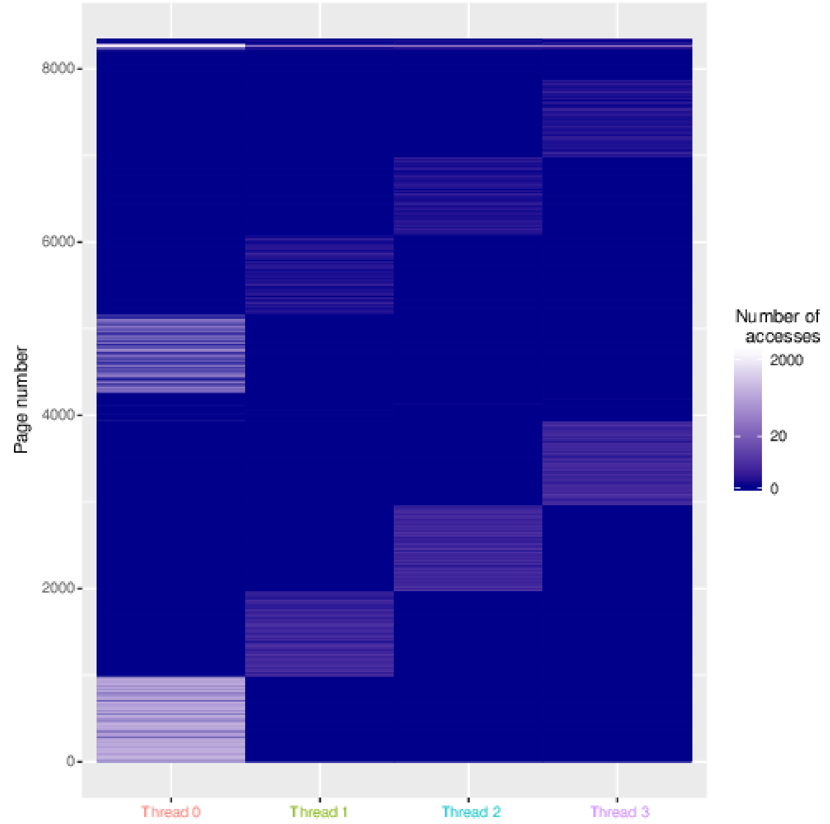
- **For each sample, find the matching memory object**
- **Once found, update counters**
  - Number of read/write accesses
  - Total cost of memory accesses to the object
- **For large objects, counters are computed per page**

- **Generate a summary of the most accessed objects**

```
Summary of the call sites:
--------------------------
Sorting call sites
0	fields_ (size=2520000) - 34098 read access (total weight: 362881, avg weight: 10.642296). 66541 wr_access
1	[stack] (size=412316860415) - 47982 read access (total weight: 345827, avg weight: 7.207432). 60001 wr_access
2	constants_ (size=1272) - 589 read access (total weight: 5131, avg weight: 8.711375). 0 wr_access
3	/usr/lib/x86_64-linux-gnu/libgomp.so.1(+0x9b49) [0x7f6b06eb4b49] (size=192) - 96 read access (total weight: 672, avg weight: 7.
```

NumaMMA
Memory access patterns

- **Access pattern to an object**
  - X-axis: threads
  - Y-axis: memory pages
- **Thread 0 access pattern**
  - Pages [0-992] [4267-5176]
- **Thread 3 access pattern**
  - Pages [993-1969] [5178-6074]
- **Due to sampling, some pages are not detected**
  - Depends on the sampling frequency

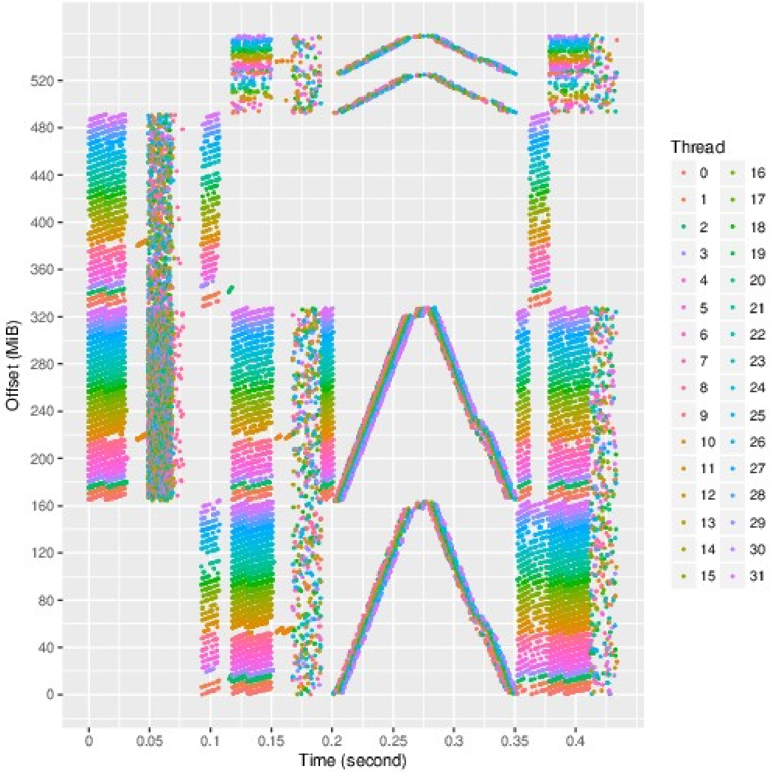


main_flt_mem in NPB CG

NumaMMA
Evolution of access patterns over the time

- **Access pattern to an object over the time**
  - X-axis: time
  - Y-axis: memory pages
  - Color: thread id

- **Allows to detect the phases of the application**



cvar in NPB LU

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Evaluation

- **Run multithreaded applications from NAS Parallel Benchmark and Parsec**
  - Evaluate the overhead
  - How to use NumaMMA to improve the execution time of applications ?
- **Experiment setup**
  - Intel32:
    - 2 Intel Xeon E5-2630 v2 CPUs (16 cores/32 threads)
    - 32 GiB RAM (2 NUMA nodes)
    - Linux 4.11, GCC 6.3
  - AMD48:
    - 4 AMD Opteron 6174 CPUs (48 cores)
    - 128 GiB RAM (8 NUMA nodes)
    - Linux 4.10, GCC 6.3

Evaluation
Overhead

- **Overhead on NAS Parallel Benchmarks**
  - Running on Intel32
  - OpenMP Implementation
  - Threads are bound
- **2 settings**
  - NumaMMA 2K
    - Sampling rate: 2000
    - Samples collected during malloc/free
  - NumaMMA 10K
    - Sampling rate 10,000
    - Sample collection every 100ms

	native	*NumaMMA_2k*			*NumaMMA_10k*		
kernel	time(s)	time(s)	ovhd(%)	nsamples	time(s)	ovhd(%)	nsamples
BT.C	81.3	82.3	1.30	0.7 M	85.7	5.46	172 M
CG.C	21.6	23.3	8.01	0.7 M	22.2	2.93	41 M
EP.C	10	10.5	3.81	0.6 M	10.5	4.40	19 M
FT.C	19.6	20.2	3.14	0.5 M	21.7	10.77	39 M
IS.C	1.5	1.48	-2.11	0.18 M	1.45	-4.35	3 M
LU.C	61.8	58	-6.11	0.65 M	61.7	-0.12	110 M
MG.C	10.4	11.3	9.01	0.8 M	10.9	5.48	22 M
SP.C	168.6	169.8	0.68	0.5 M	169.6	0.59	334 M
UA.C	86.6	93.5	8.00	0.6 M	96.5	11.37	171 M

→ **Low overhead**

→ **High resolution of a subset vs. Low resolution of the whole application**

Evaluation
Case study: NPB LU

- **Application: NPB LU**
  - LU matrix factorization
  - OpenMP Implementation
- **Most accessed objects:**

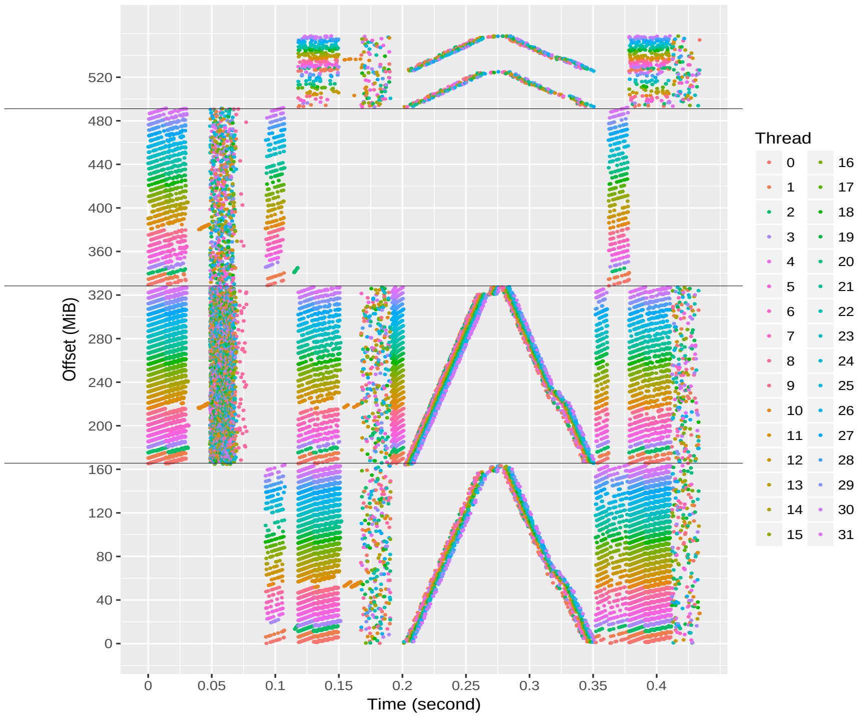
symbol	*size*	*nb read*	*nb write*	*total*	*percent*
cvar	558 MB	112k	118k	230k	35.4
stack	?	105k	124k	229k	35.2
cexact	520 B	86k	0	86k	13.2
cjac	20 MB	39k	54k	94k	14.4
libgomp.so.1(+0x97c9)	8 KB	4k	97	4k	0.7

- **Access pattern analysis**
  - `cexact` is accessed evenly by the threads → no easy optimization
  - `cvar` and `cjac` could be optimized

Evaluation

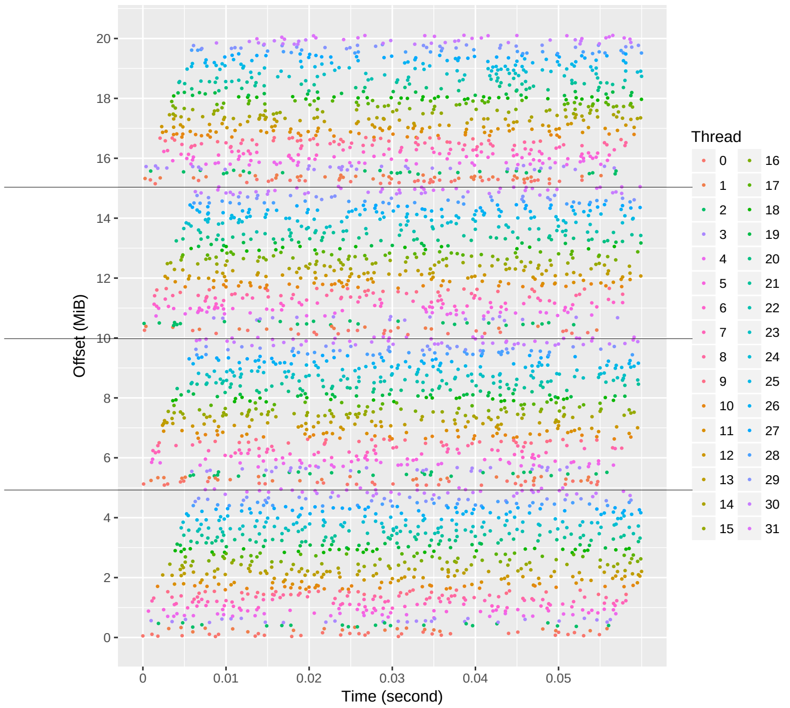
NPB LU: Analyzing the access pattern

- **`cvar`**
  - 558MiB buffer
  - Accessed by slices of 160MiB
  - → **block-cyclic distribution**



Access pattern to cvar

- **`cjac`**
  - 20MiB buffer
  - Accessed by slices of 5MiB
  - → **block-cyclic distribution**



Access pattern to cjac

Evaluation
NPB LU: optimizing memory placement

- **Evaluation on AMD48**
- **Comparing different memory placement**
  - First-touch: default policy
  - Interleaved: interleave the memory pages of `cvar` and `cjac`
  - Block-naive: use a block distribution for `cvar` and `cjac`
  - NumaMMA: place `cvar` and `cjac` using a block-cyclic distribution

policy	execution time(s)	speedup
first-touch	102.53	1
interleaved	106.86	0.96
block-naive	109.88	0.93
NumaMMA	81.05	1.27

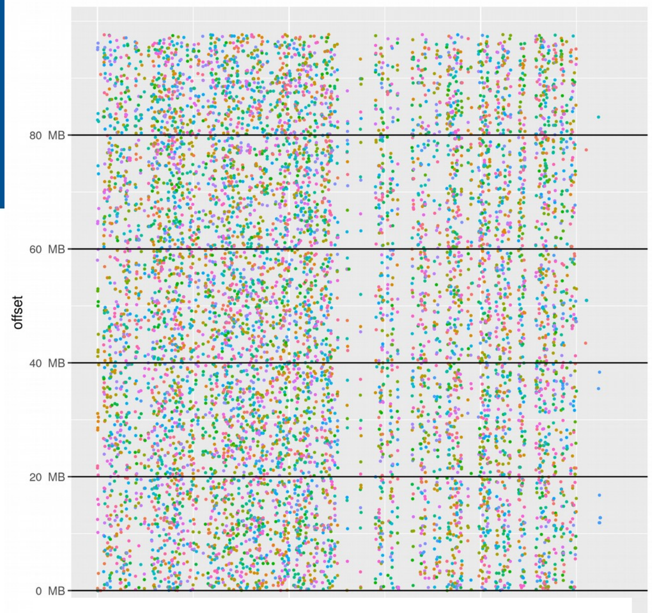
→ 27% performance improvement

Evaluation
Case study: Streamcluster

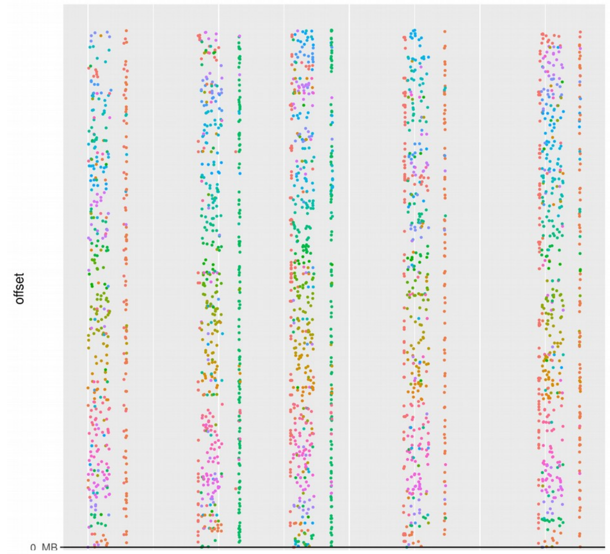
- **Application: Parsec Streamcluster**
- **Most accessed objects**
  - `block` – 98 MiB buffer (66% of the samples)
    - Evenly distributed accesses
      → interleave pages
  - `points` – 6 MiB buffer (31% of the samples)
    - Each thread accesses a part of the buffer
      → block distribution
- **Evaluation**

policy	execution time(s)	speedup
first-touch	93.72	1
interleaved	76.76	1.22
block-naive	79.75	1.17
NumaMMA	73.32	1.28

- → 28 % improvement



Access pattern to block



Access pattern to points

Conclusion & future work

- **Memory placement is important for performance**
- **NumaMMA: NUMA MeMory Analyzer**
  - Use hardware sampling to collect memory access samples
  - Report the most accessed memory objects
  - Report the threads access pattern over the time
  - Available as open-source: https://github.com/numamma/numamma
- **Evaluation**
  - Low overhead (< 12%)
  - Reported information can be used for improving performance by up to 28%

- **Future work**
  - Port over AMD cpus
  - Use a signal to handle overflows
  - Automate memory placement

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