PufferFish: NUMA-Aware Work-stealing Library using Elastic Tasks

Vivek Kumar

IIIT New Delhi, India

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.
6.           Sort(/*Chunk C1*/);
7.           Sort(/*Chunk C2*/);
8.           Sort(/*Chunk C3*/);
9.           Sort(/*Chunk C4*/);
10.
11.
12.          Merge(/*Chunk C1*/, /*Chunk C2*/);
13.          Merge(/*Chunk C3*/, /*Chunk C4*/);
14.
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```

Multicore Processor

Task Parallelism on Multicore Processors

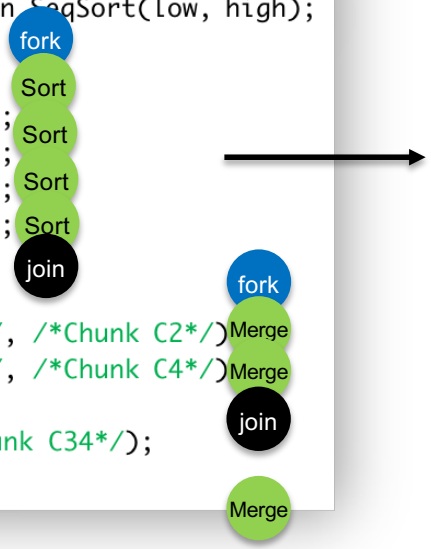
```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```

Serial elision
High **productivity**

Multicore Processor

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```

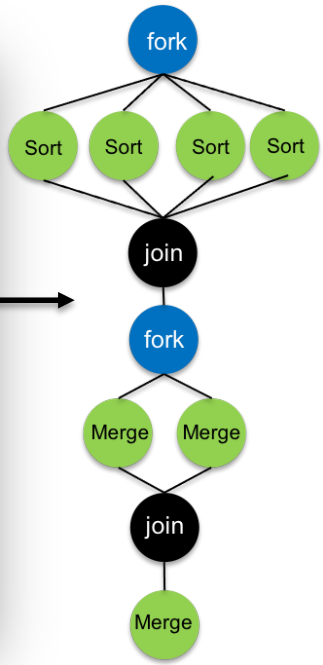


Serial elision
High **productivity**

Multicore Processor

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



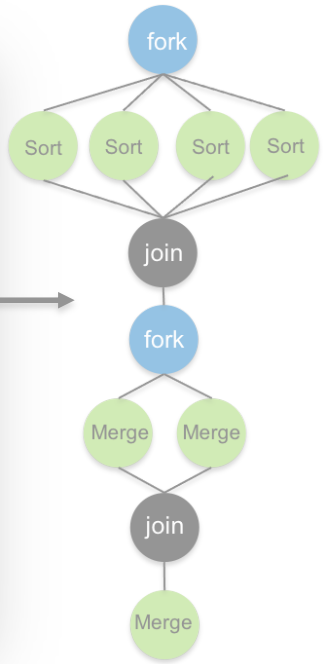
Multicore Processor

Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



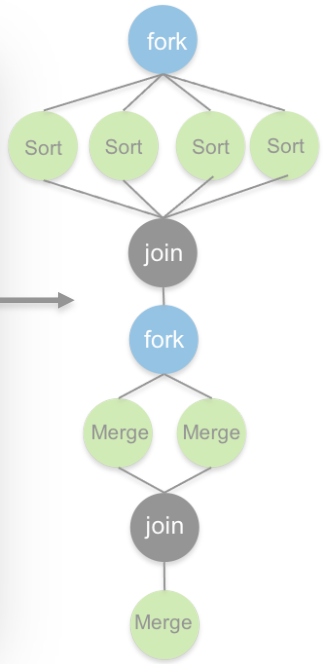
Multicore Processor

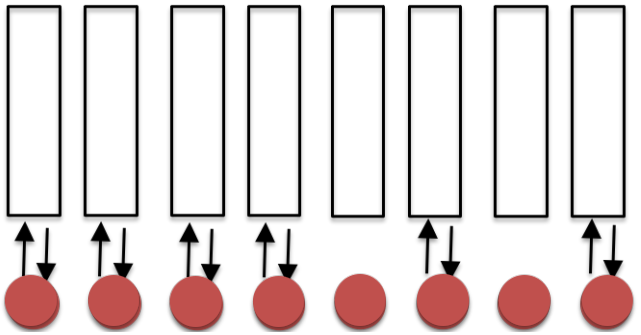
Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





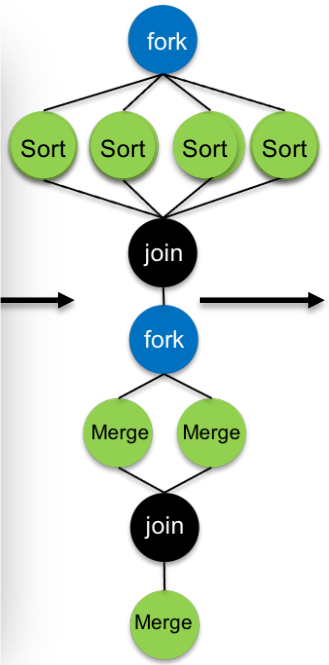
Multicore Processor

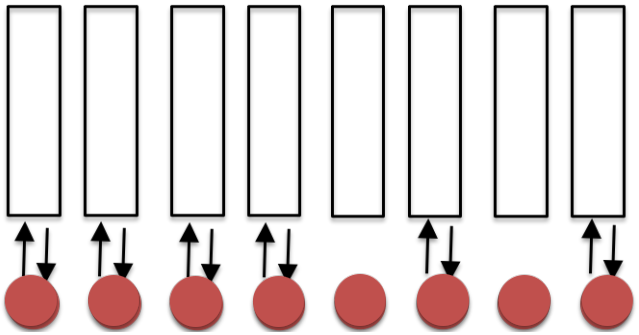
Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





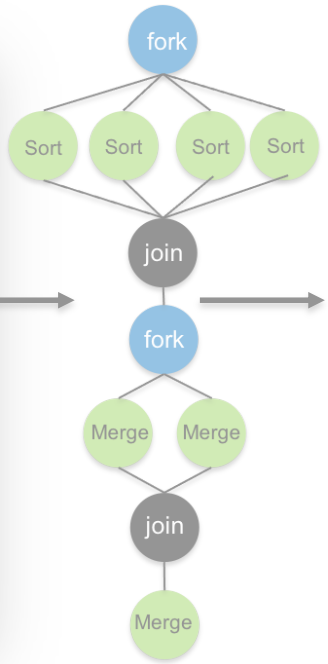
Multicore Processor

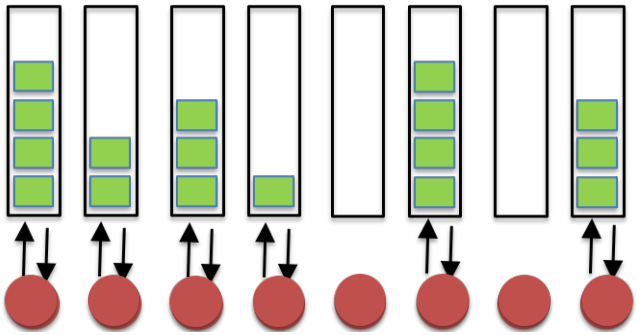
Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





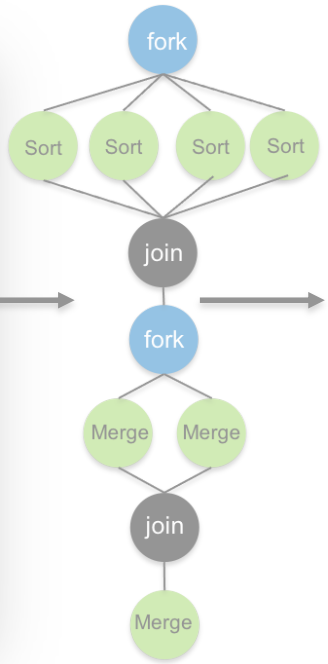
Multicore Processor

Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



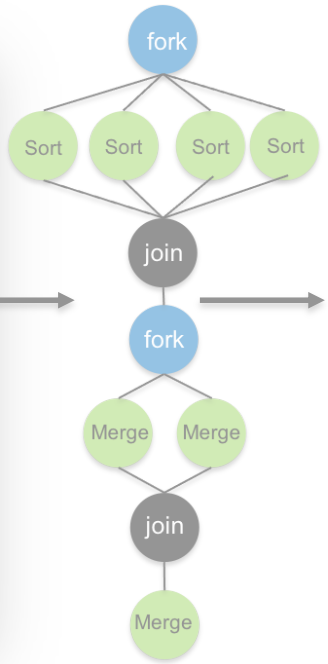
Multicore Processor

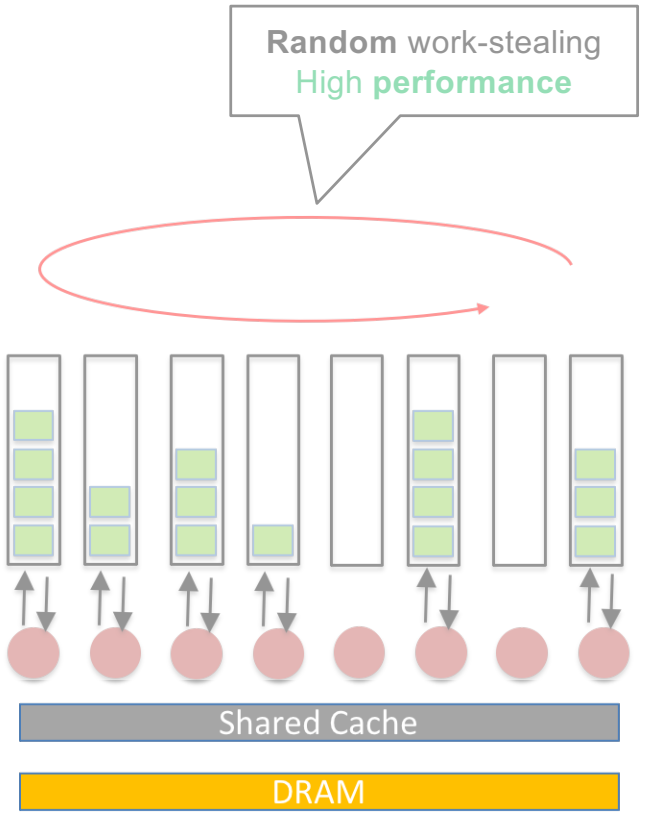
Serial elision
High **productivity**

Irregular
execution DAG

Task Parallelism on **UMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





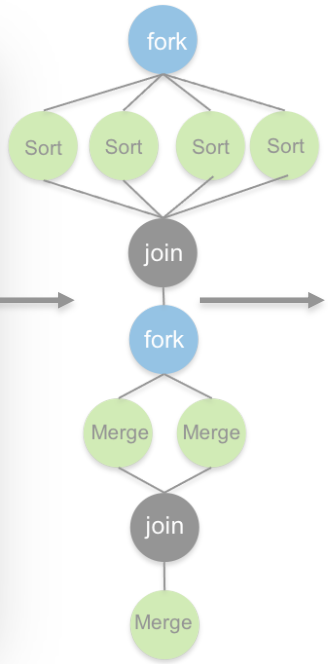
Serial elision
High **productivity**

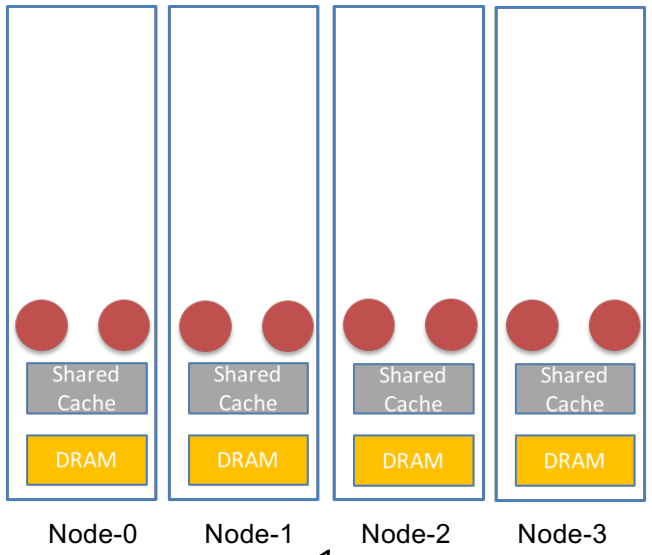
Irregular
execution DAG

Uniform Memory Access
(**UMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





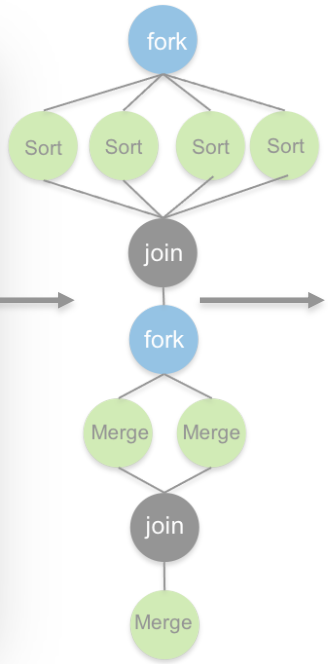
Serial elision
High **productivity**

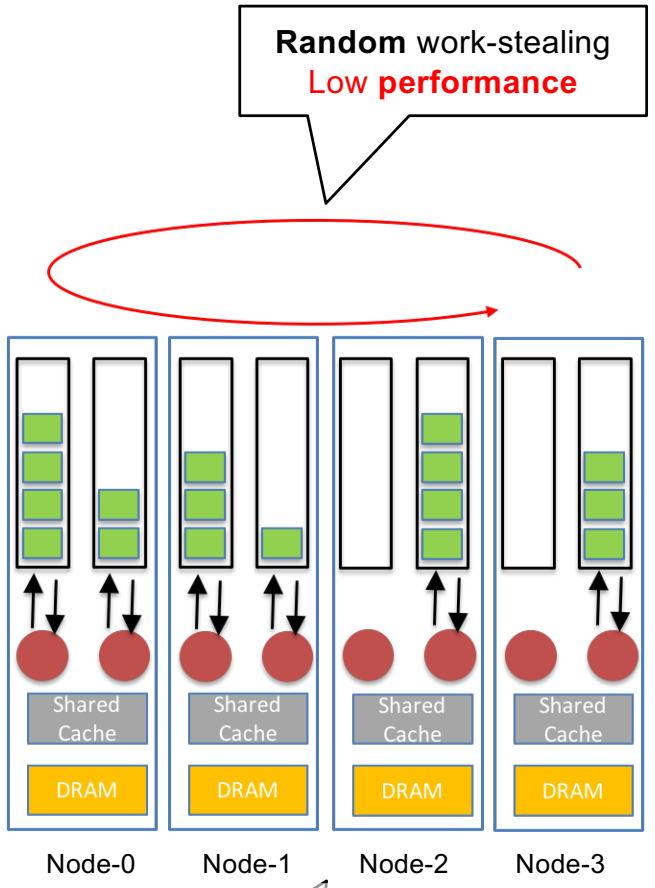
Irregular
execution DAG

Non Uniform Memory Access
(**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async Sort(/*Chunk C1*/);
7.     async Sort(/*Chunk C2*/);
8.     async Sort(/*Chunk C3*/);
9.     async Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





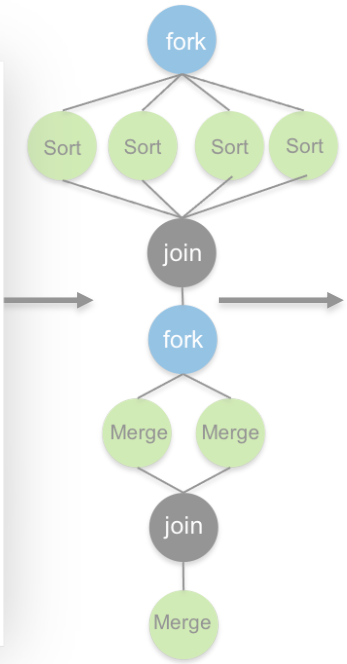
Serial elision
High **productivity**

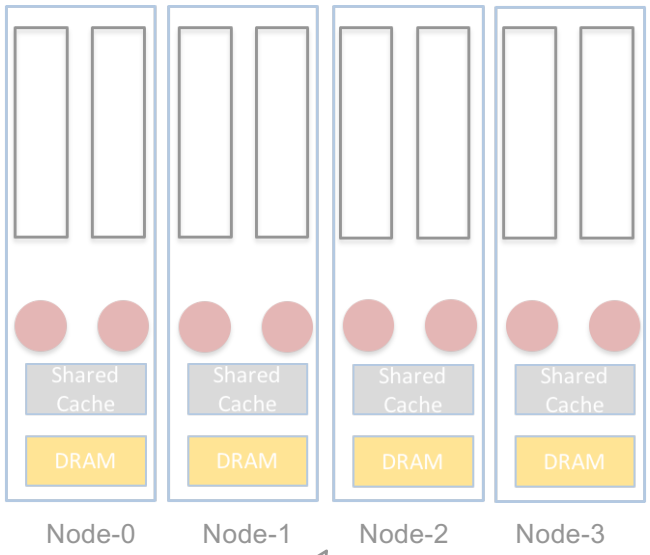
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





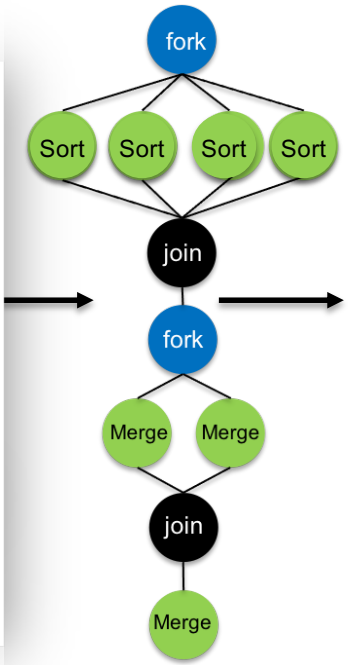
Serial elision
High **productivity**

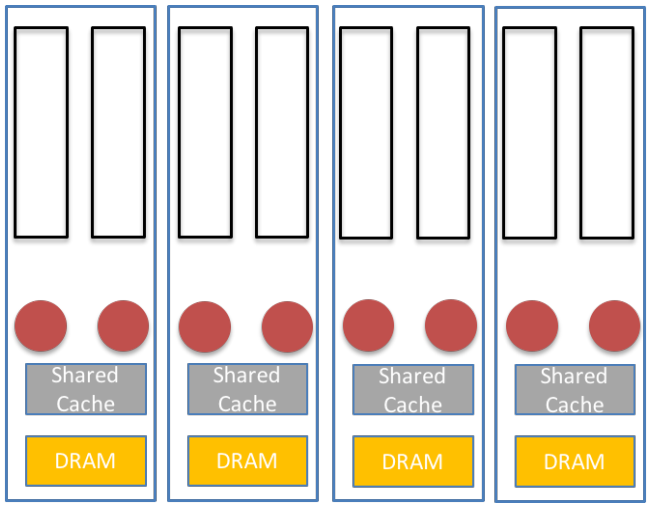
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





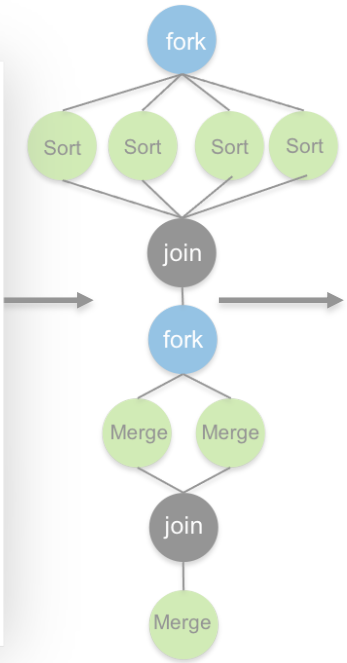
Serial elision
High **productivity**

Irregular execution DAG

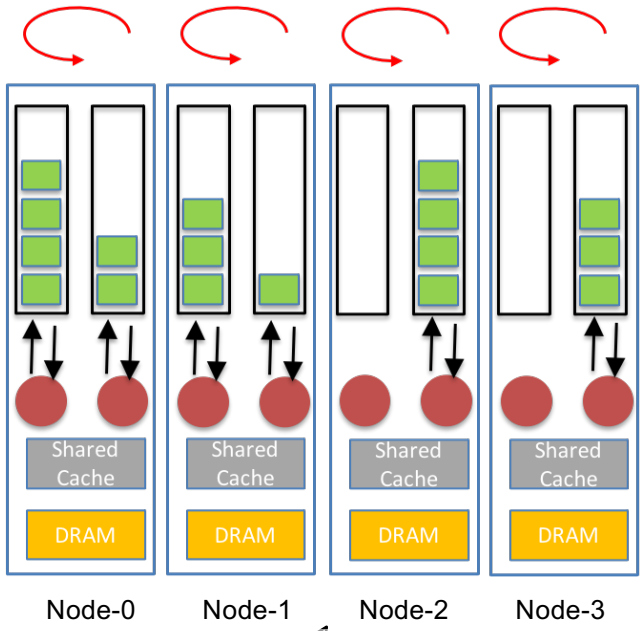
Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



Hierarchical work-stealing
High Performance



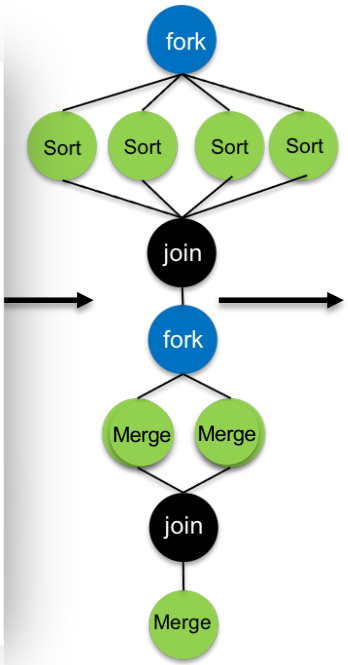
Serial elision
High **productivity**

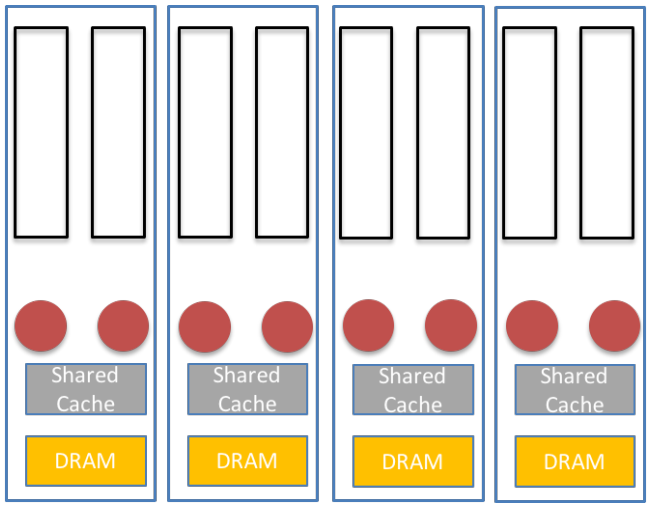
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





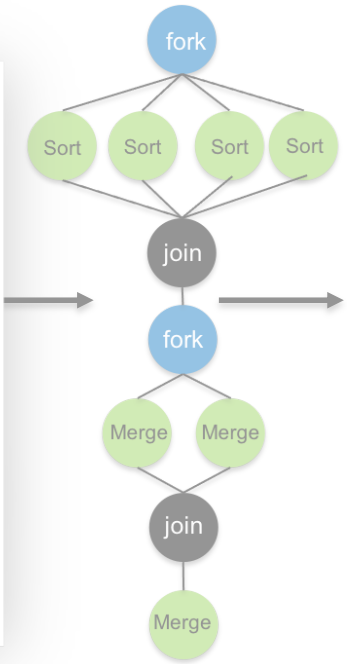
Serial elision
High **productivity**

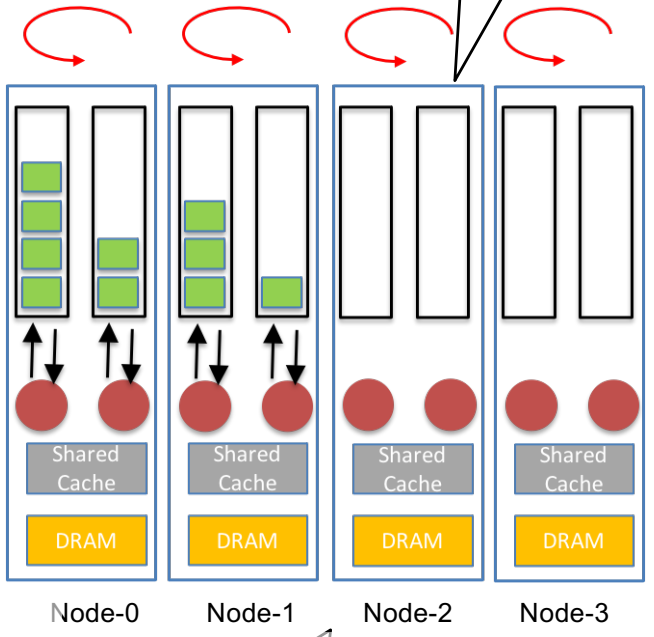
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





Hierarchical work-stealing
1. Worker Starvation

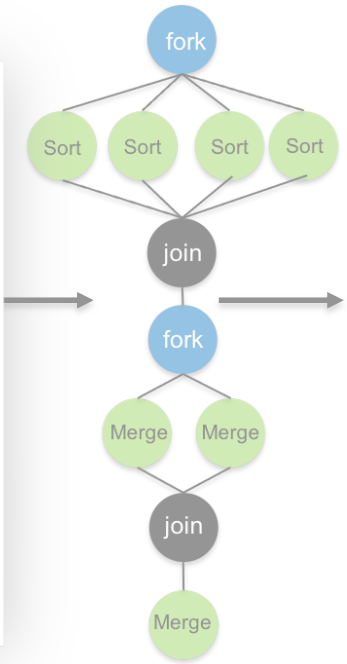
Serial elision
High **productivity**

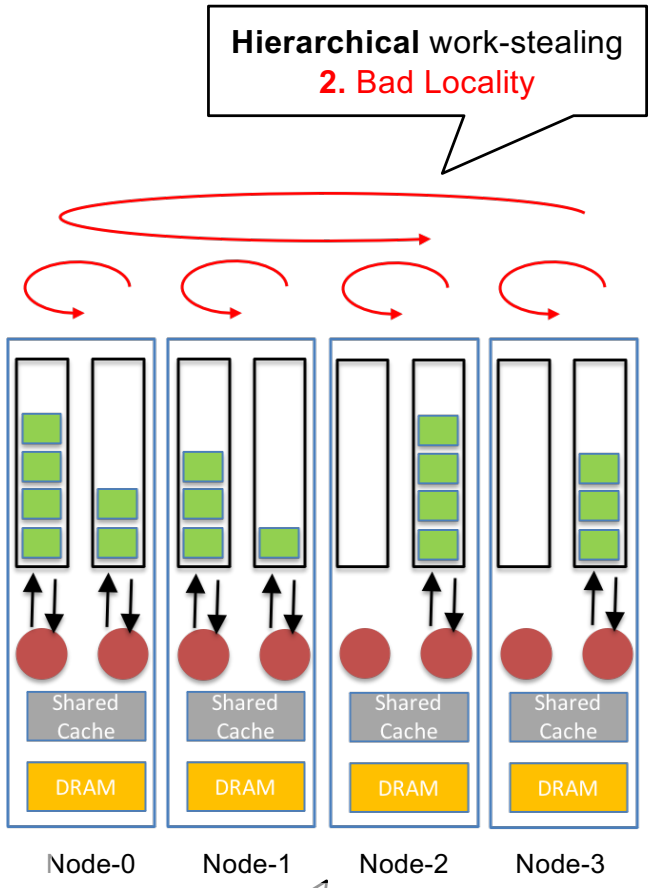
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





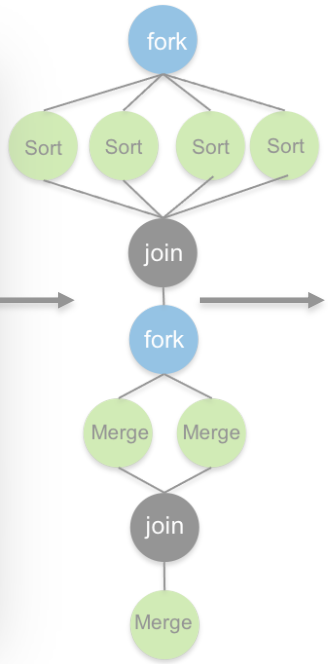
Serial elision
High **productivity**

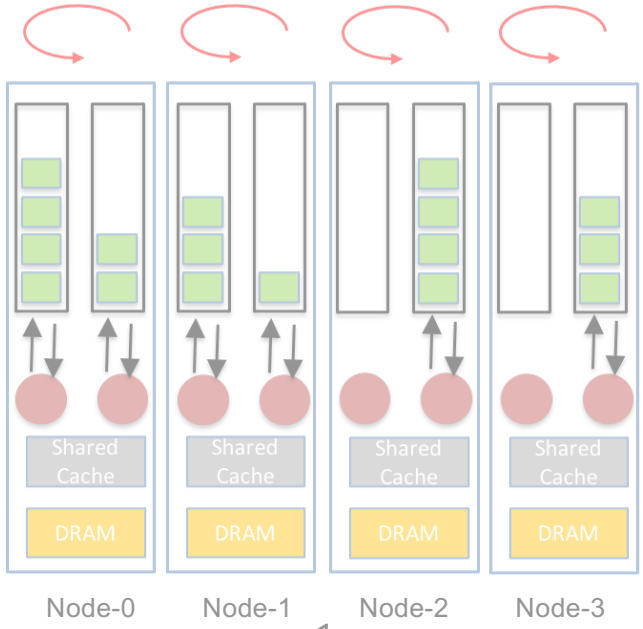
Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Task Parallelism on **NUMA** Multicore Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_at(0) Sort(/*Chunk C1*/);
7.     async_at(1) Sort(/*Chunk C2*/);
8.     async_at(2) Sort(/*Chunk C3*/);
9.     async_at(3) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_at(0) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_at(1) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```





Hierarchical work-stealing
High Performance

Modify ”merge” into four subtask

3. No Serial elision

Irregular execution DAG

Non Uniform Memory Access (**NUMA**)

Contribution: PufferFish

Library for Task Parallelism & Work-Stealing over NUMA Processors

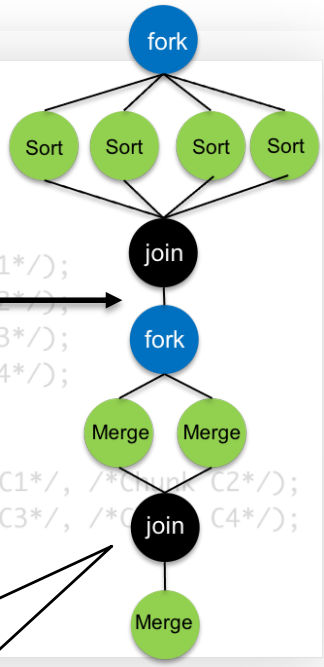
```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_hinted (A, C1_start, C1_end) Sort(/*Chunk C1*/);
7.     async_hinted (A, C2_start, C2_end) Sort(/*Chunk C2*/);
8.     async_hinted (A, C3_start, C3_end) Sort(/*Chunk C3*/);
9.     async_hinted (A, C4_start, C4_end) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_hinted (A, C1_start, C2_end) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_hinted (A, C3_start, C4_end) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```

1. **Supports Serial elision**
(except for using NUMA aware malloc/free)

Contribution: PufferFish

Library for Task Parallelism & Work-Stealing over NUMA Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_hinted (A, C1_start, C1_end) Sort(/*Chunk C1*/);
7.     async_hinted (A, C2_start, C2_end) Sort(/*Chunk C2*/);
8.     async_hinted (A, C3_start, C3_end) Sort(/*Chunk C3*/);
9.     async_hinted (A, C4_start, C4_end) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_hinted (A, C1_start, C2_end) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_hinted (A, C3_start, C4_end) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



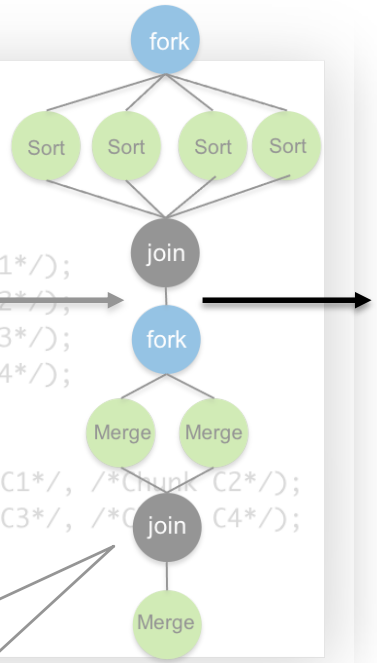
2. Supports Irregular execution DAG

1. Supports Serial elision
(except for using NUMA aware malloc/free)

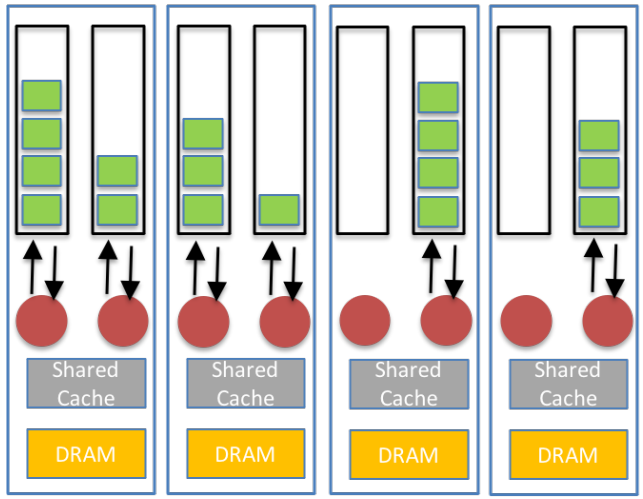
Contribution: PufferFish

Library for Task Parallelism & Work-Stealing over NUMA Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_hinted (A, C1_start, C1_end) Sort(/*Chunk C1*/);
7.     async_hinted (A, C2_start, C2_end) Sort(/*Chunk C2*/);
8.     async_hinted (A, C3_start, C3_end) Sort(/*Chunk C3*/);
9.     async_hinted (A, C4_start, C4_end) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_hinted (A, C1_start, C2_end) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_hinted (A, C3_start, C4_end) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



Hierarchical work-stealing
3. Improves Locality
4. Removes Starvation



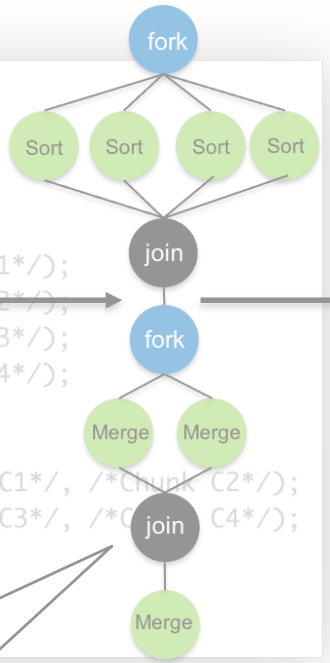
2. Supports Irregular execution DAG

1. Supports Serial elision
(except for using NUMA aware malloc/free)

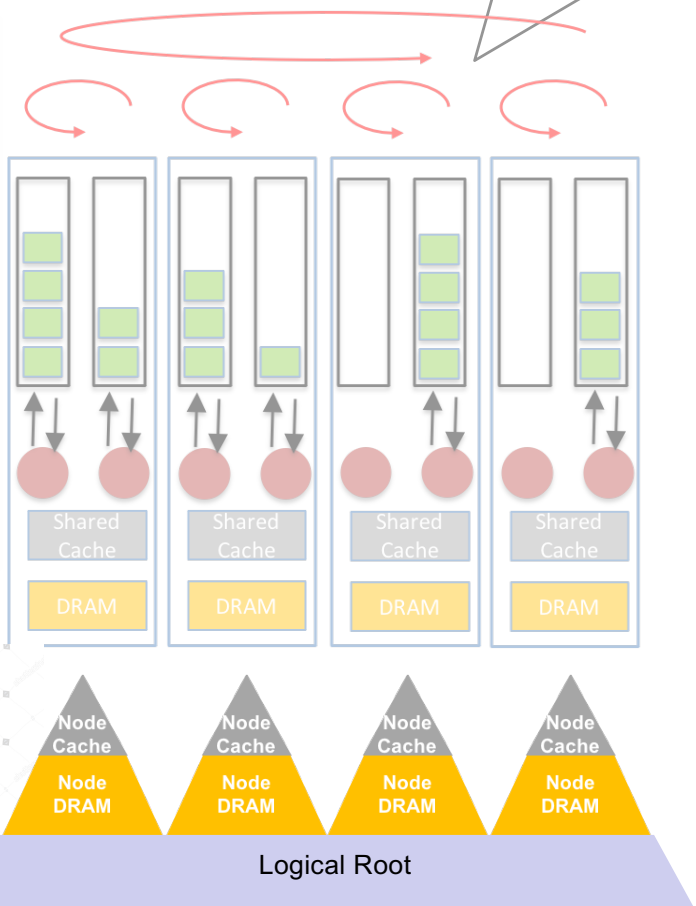
Contribution: PufferFish

Library for Task Parallelism & Work-Stealing over NUMA Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_hinted (A, C1_start, C1_end) Sort(/*Chunk C1*/);
7.     async_hinted (A, C2_start, C2_end) Sort(/*Chunk C2*/);
8.     async_hinted (A, C3_start, C3_end) Sort(/*Chunk C3*/);
9.     async_hinted (A, C4_start, C4_end) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_hinted (A, C1_start, C2_end) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_hinted (A, C3_start, C4_end) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



Hierarchical work-stealing
3. Improves Locality
4. Removes Starvation



NUMA Memory Hierarchy

2. Supports Irregular execution DAG

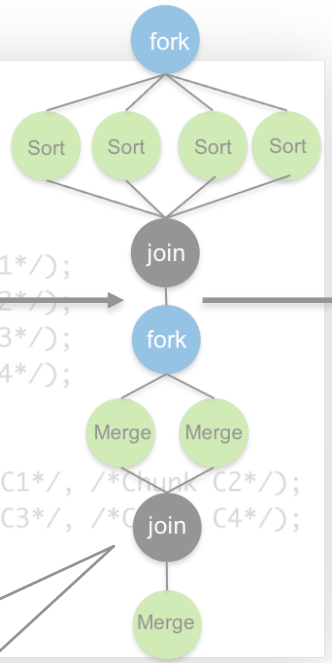
1. Supports Serial elision
(except for using NUMA aware malloc/free)

5. Hierarchical Elastic Tasks
(further improves the locality)

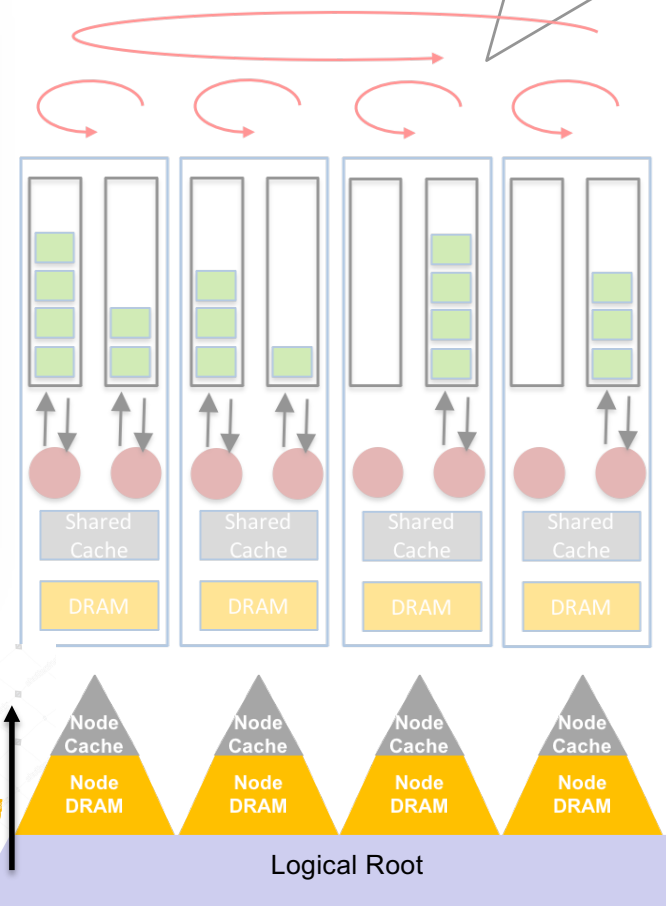
Contribution: PufferFish

Library for Task Parallelism & Work-Stealing over NUMA Processors

```
1. int *A;
2. void Sort(int low, int high) {
3.   if((high-low)<LIMIT) return SeqSort(low, high);
4.   int Chunks=(high-low)/4;
5.   finish {
6.     async_hinted (A, C1_start, C1_end) Sort(/*Chunk C1*/);
7.     async_hinted (A, C2_start, C2_end) Sort(/*Chunk C2*/);
8.     async_hinted (A, C3_start, C3_end) Sort(/*Chunk C3*/);
9.     async_hinted (A, C4_start, C4_end) Sort(/*Chunk C4*/);
10.  }
11.  finish {
12.    async_hinted (A, C1_start, C2_end) Merge(/*Chunk C1*/, /*Chunk C2*/);
13.    async_hinted (A, C3_start, C4_end) Merge(/*Chunk C3*/, /*Chunk C4*/);
14.  }
15.  Merge(/*Chunk C12*/, /*Chunk C34*/);
16.}
```



Hierarchical work-stealing
3. Improves Locality
4. Removes Starvation



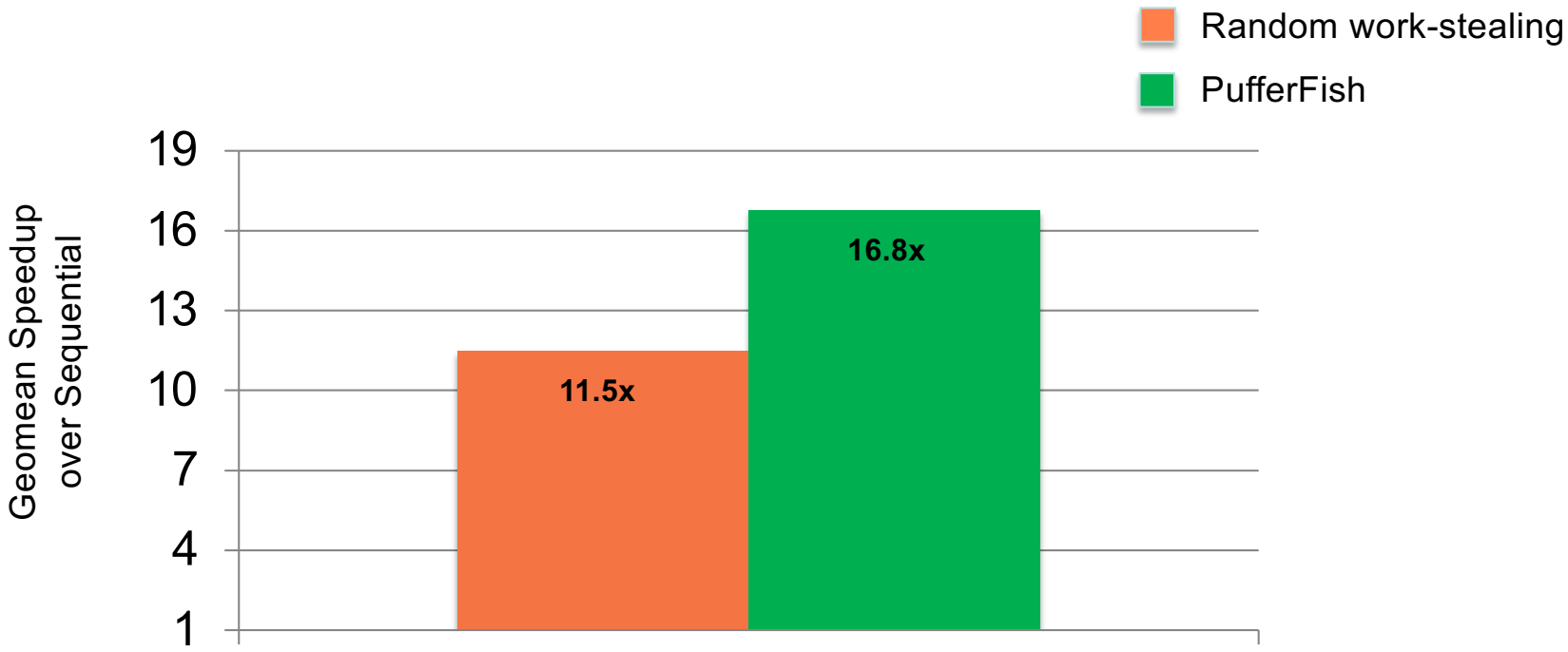
NUMA Memory Hierarchy

2. Supports Irregular execution DAG

1. Supports Serial elision
(except for using NUMA aware malloc/free)

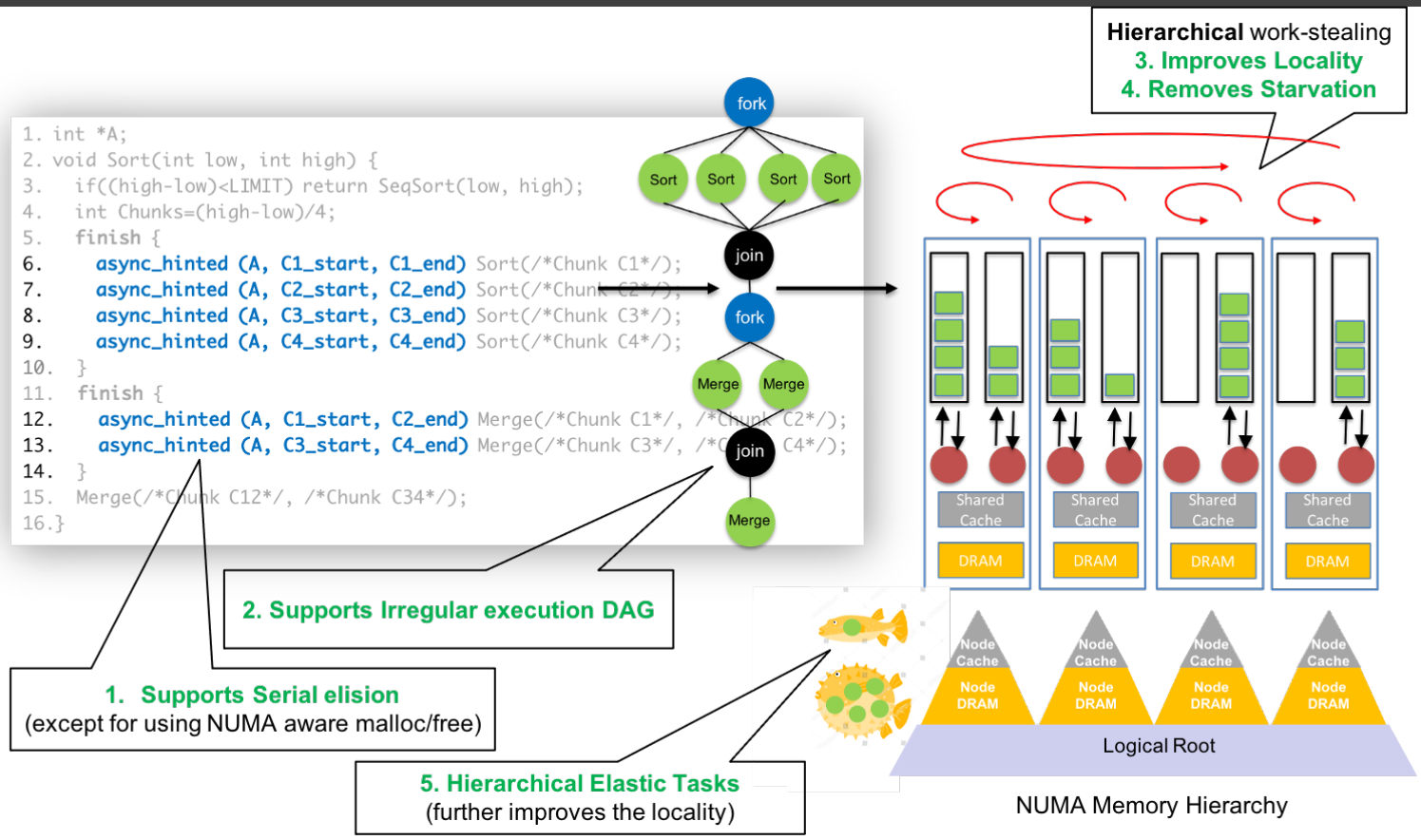
5. Hierarchical Elastic Tasks
(further improves the locality)

Performance Analysis on AMD EPYC 7551



Executing summary for **seven** recursive benchmarks with regular/irregular DAG on a **32-core** processor with **four** NUMA nodes

Thank you



Artifact