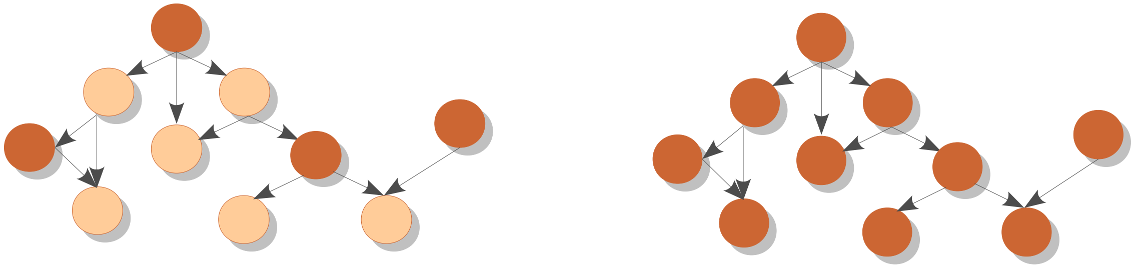
Data-driven versus Topology-driven Irregular Computations on GPUs



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IPDPS 2013

What is IrReguLariTy?

- Data-access or control patterns are unpredictable at compile time.

Irregular data-access

```
int a[N], b[N], c[N];
readinput(a);

c[5] = b[a[4]];
```

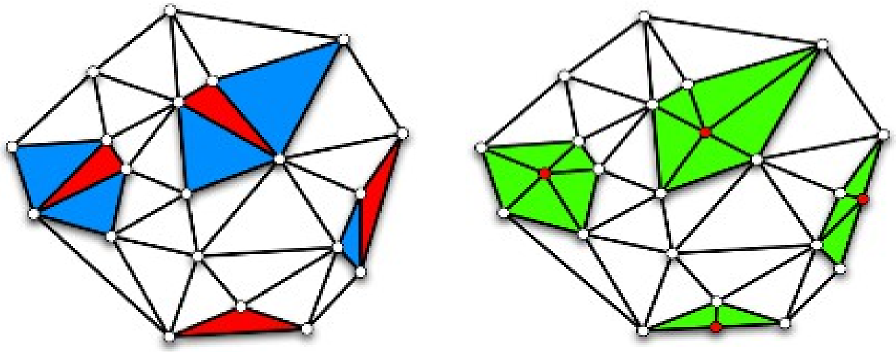
Irregular control-flow

```
int a[N];
readinput(a);

if (a[4] > 30) {
        ...
}
```

Needs dynamic techniques

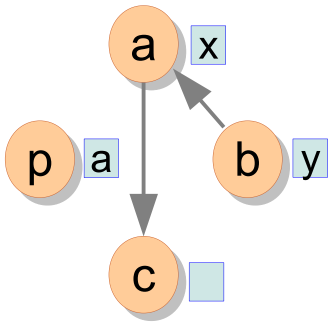
Pointer-based data structures often contribute to irregularity.

Examples of Irregular Programs

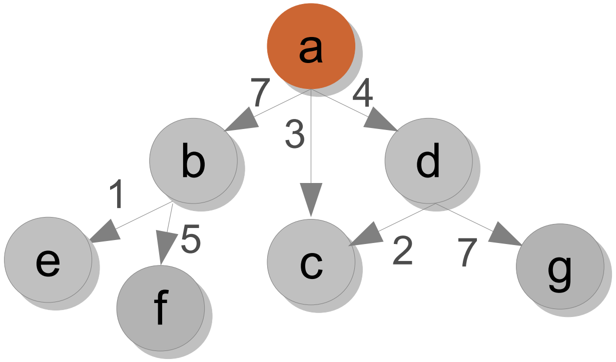


Delaunay Mesh Refinement

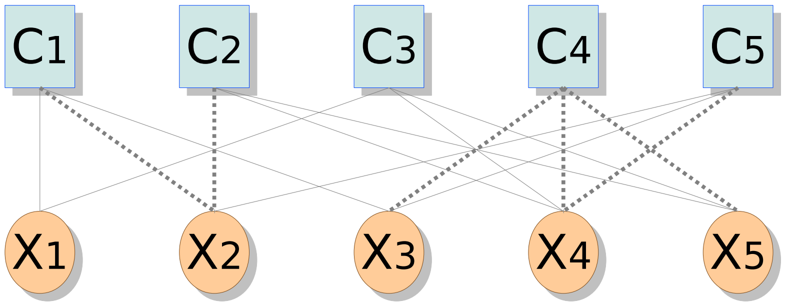
```
a = &x
b = &y
p = &a
*p = b
c = a
```



Points-to Analysis

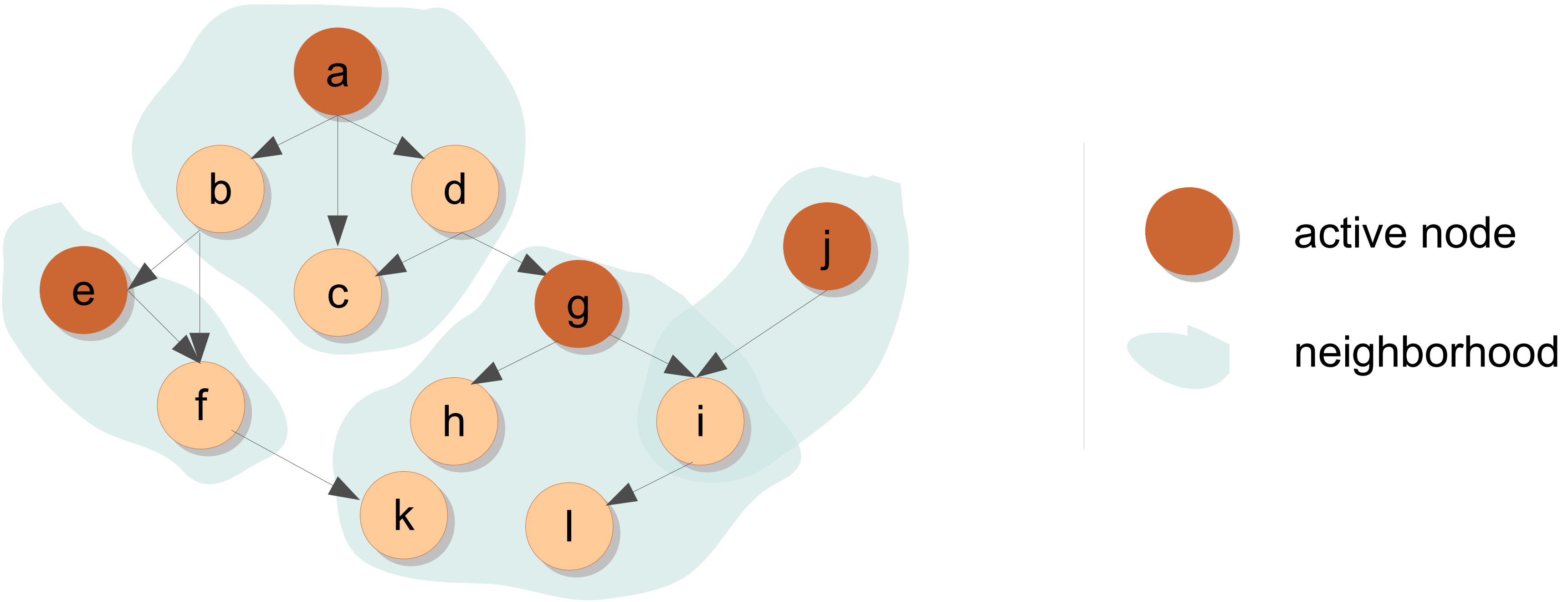


Single-source shortest paths



Survey Propagation

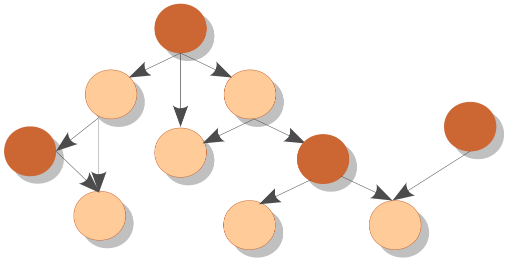
Operator Formulation



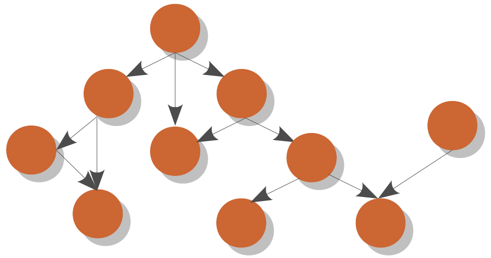
- Computation is modeled as an iterated application of an operator
- **Data-driven processing**: operator is applied only at the nodes where there might be work to be done
- **Topology-driven processing**: operator is applied at all the nodes even if there is no work to do at some nodes

Focus of This Work

- **Study and optimize** topology-driven and data-driven irregular computations on GPUs
    - On GPUs, irregular algorithms are usually implemented in a topology-driven manner
    - On multi-core CPUs, irregular algorithms are usually implemented in a data-driven manner
- **Our findings**
    - Data-driven versions usually perform better
    - Topology-driven versions perform better if additional algorithmic properties can be exploited
    - A hybrid approach can outperform the two



data-driven



topology-driven

Outline

- Motivation

➔ **Data-driven approach**

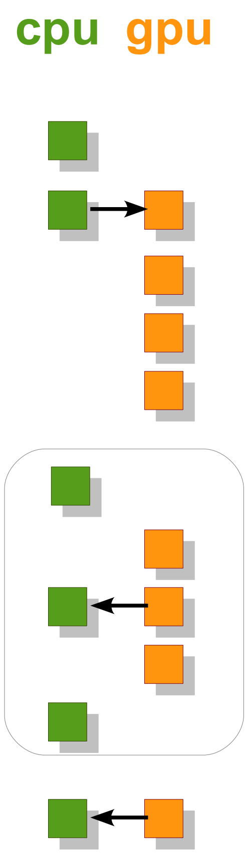
- Topology-driven approach
- Hybrid approach
- Evaluation
- Conclusions

Outline

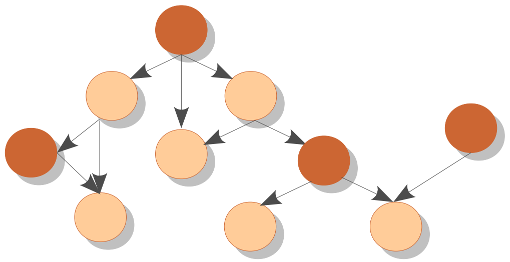
- Motivation
- ➔ **Data-driven approach**
  - dual-worklist
  - hierarchical worklists
  - work-chunking
  - atomic-free worklist update
  - work-donation
  - variable kernel configuration
- Topology-driven approach
- Hybrid approach
- Evaluation
- Conclusions

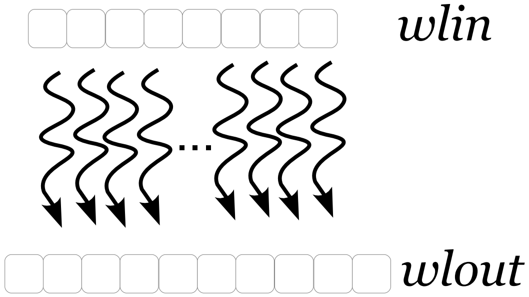
Data-driven: Base Version

```
main {
    read input
    transfer input
    initialize_kernel
    initialize_worklist(wlin)
    clear wlout

    while wlin not empty {
        operator(wlin, wlout, ...)
        transfer wlout size
        clear wlin
        swap(wlin, wlout)
    }
    transfer results
}
```

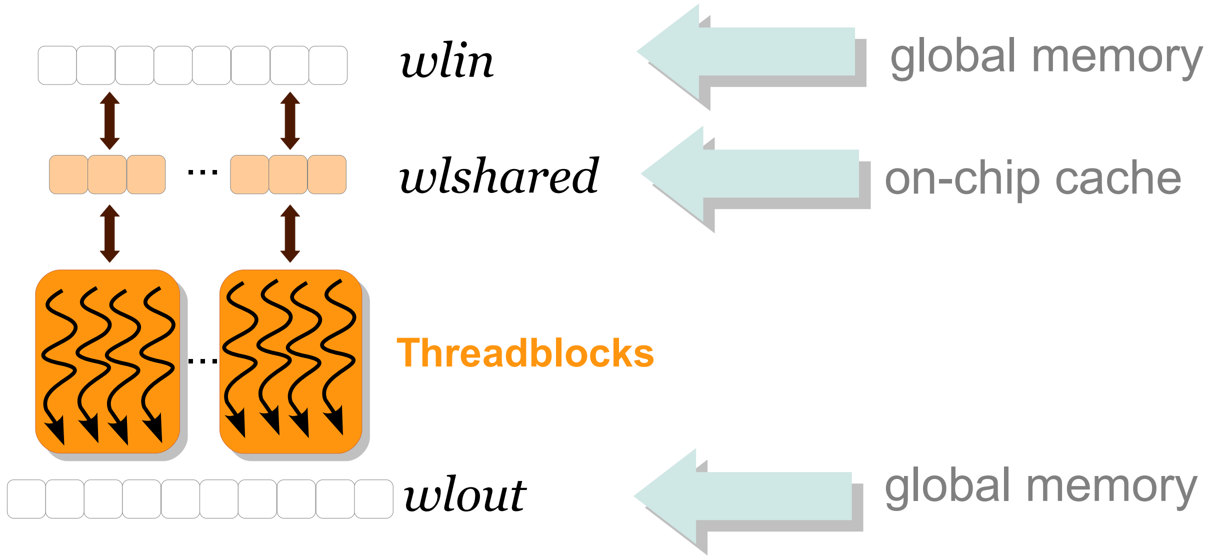


```
sssp_operator(wlin, wlout, ...) {
    src = wlin[...]
    dsrc = distance[src]
    forall edges (src, dst, wt) {
        ddst = distance[dst]
        altdist = dsrc + wt

        if altdist < ddst
            distance[dst] = altdist
            wlout.push(dst)
} }
```



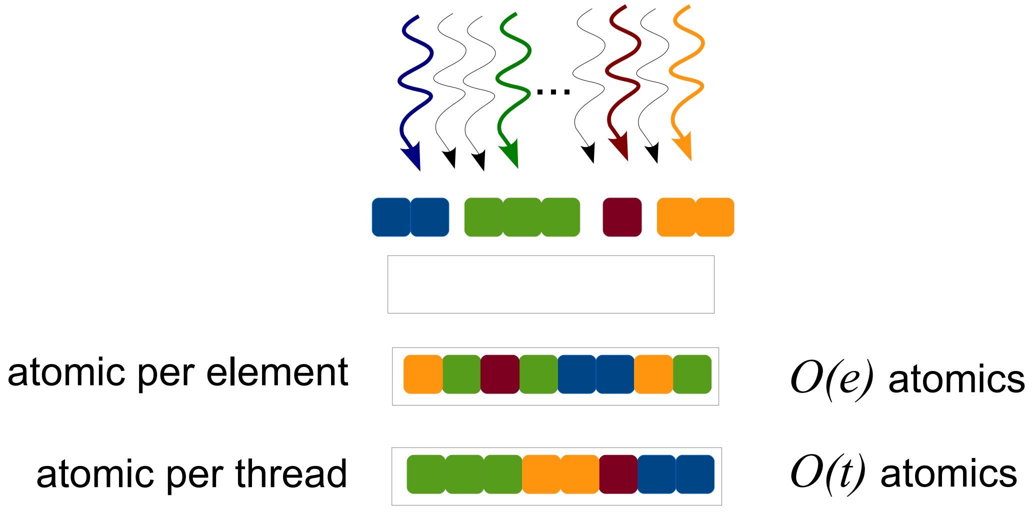


Data-driven: Hierarchical Worklist



- Worklist exploits memory hierarchy
- Makes judicious use of limited on-chip cache

Data-driven: Work Chunking

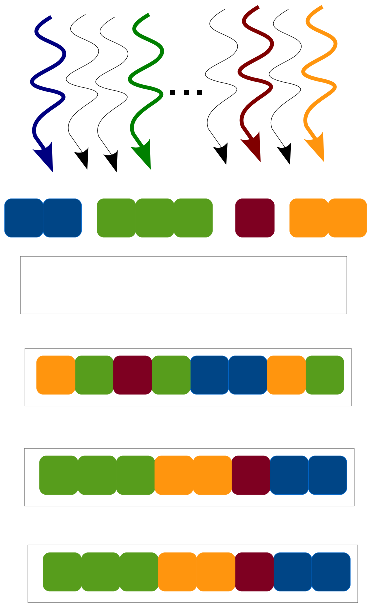


atomic per element $O(e)$ atomics

atomic per thread $O(t)$ atomics

- Reserves space for multiple work-items in a single atomic
- May reduce overall synchronization

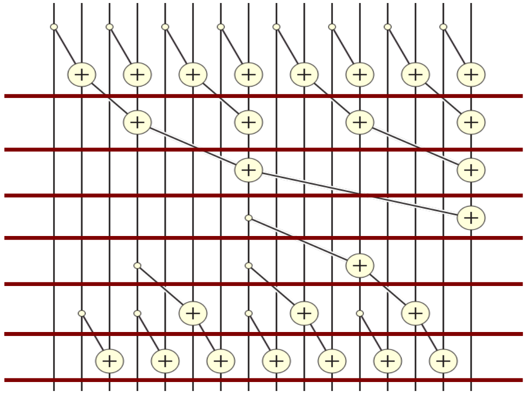
Data-driven: Atomic-free Worklist Update



atomic per element — $O(e)$ atomics

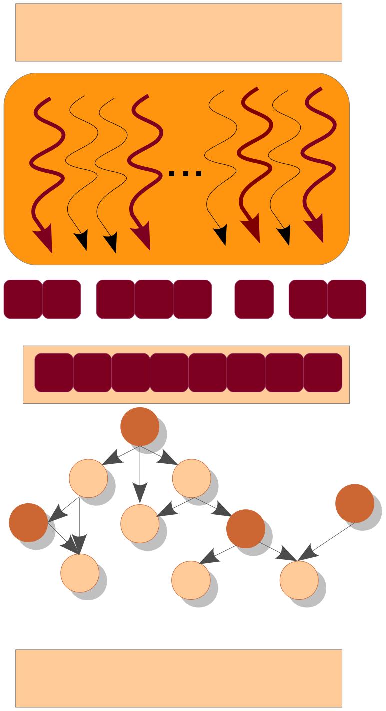
atomic per thread — $O(t)$ atomics

prefix-sum — $O(\log t)$ barriers



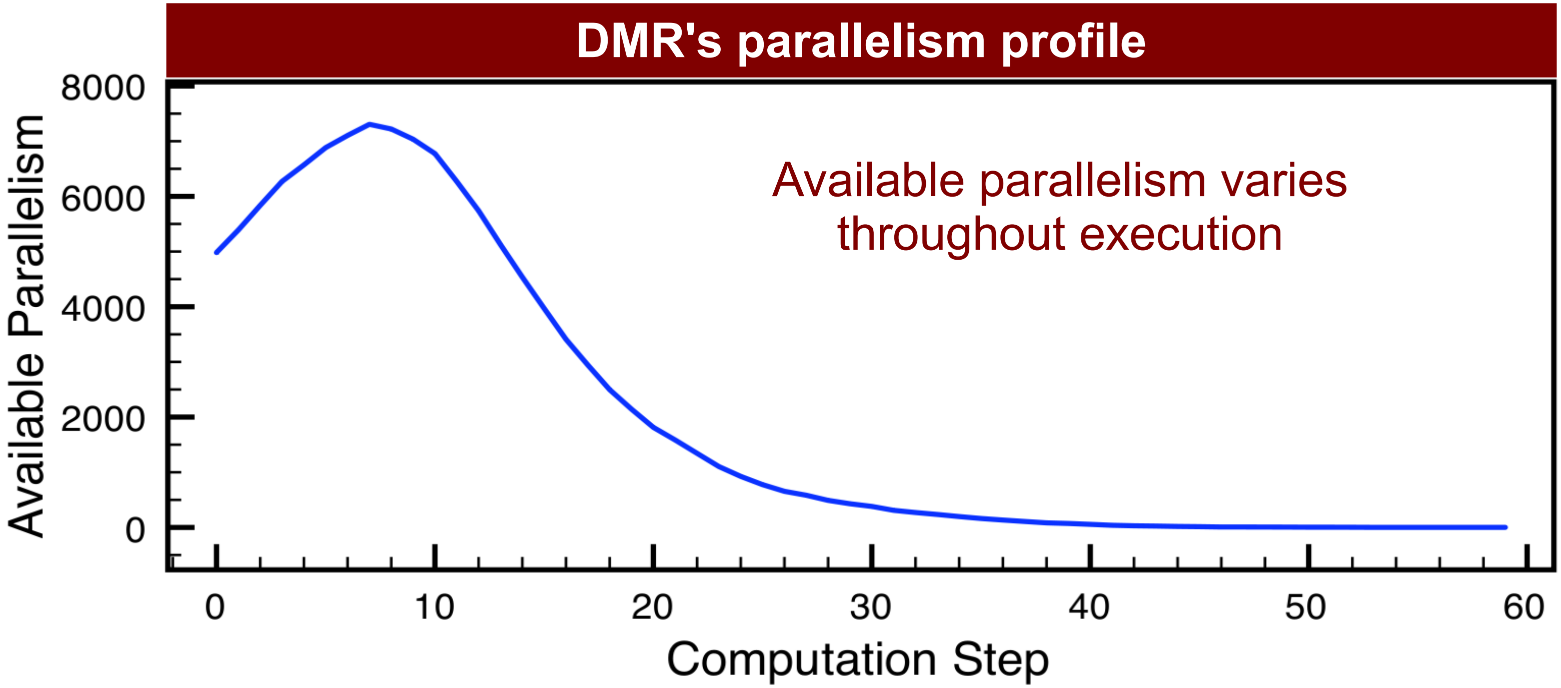
Data-driven: Work Donation

```
donate_kernel {
        shared donationbox[...];


        // determine if I should donate
        --barrier--

        // donate
        --barrier--

        // operator execution


        // empty donation box

}
```



- Work-donation improves load balance

Data-driven: Variable Kernel Configuration



- Varying configuration improves work-efficiency
- It also reduces conflicts and may improve performance

Outline

- Motivation
- Data-driven approach

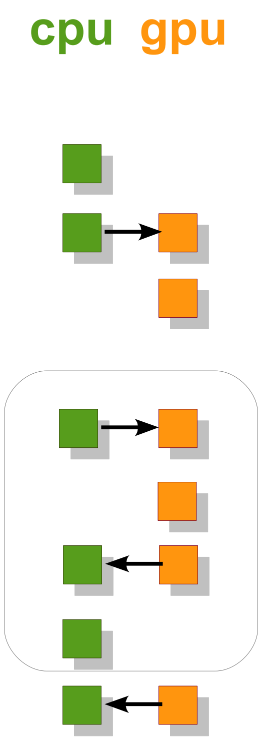
→ **Topology-driven approach**

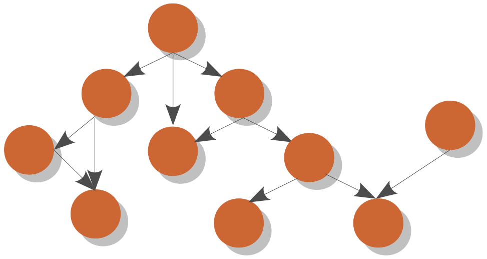
  - no global worklists
  - kernel unrolling
  - exploiting memory hierarchy
  - improved memory layout

- Hybrid approach
- Evaluation
- Conclusions

Topology-driven: Base Version

```
main {
    read input
    transfer input
    initialize_kernel
    do {
        transfer false to changed
        operator(...)
        transfer changed
    } while changed
    transfer results
}
```

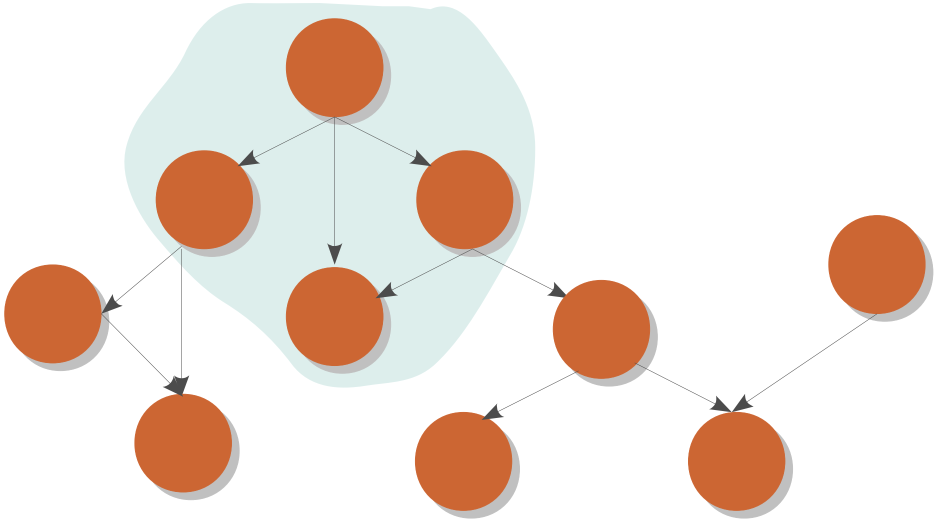




Topology-driven: Kernel Unrolling

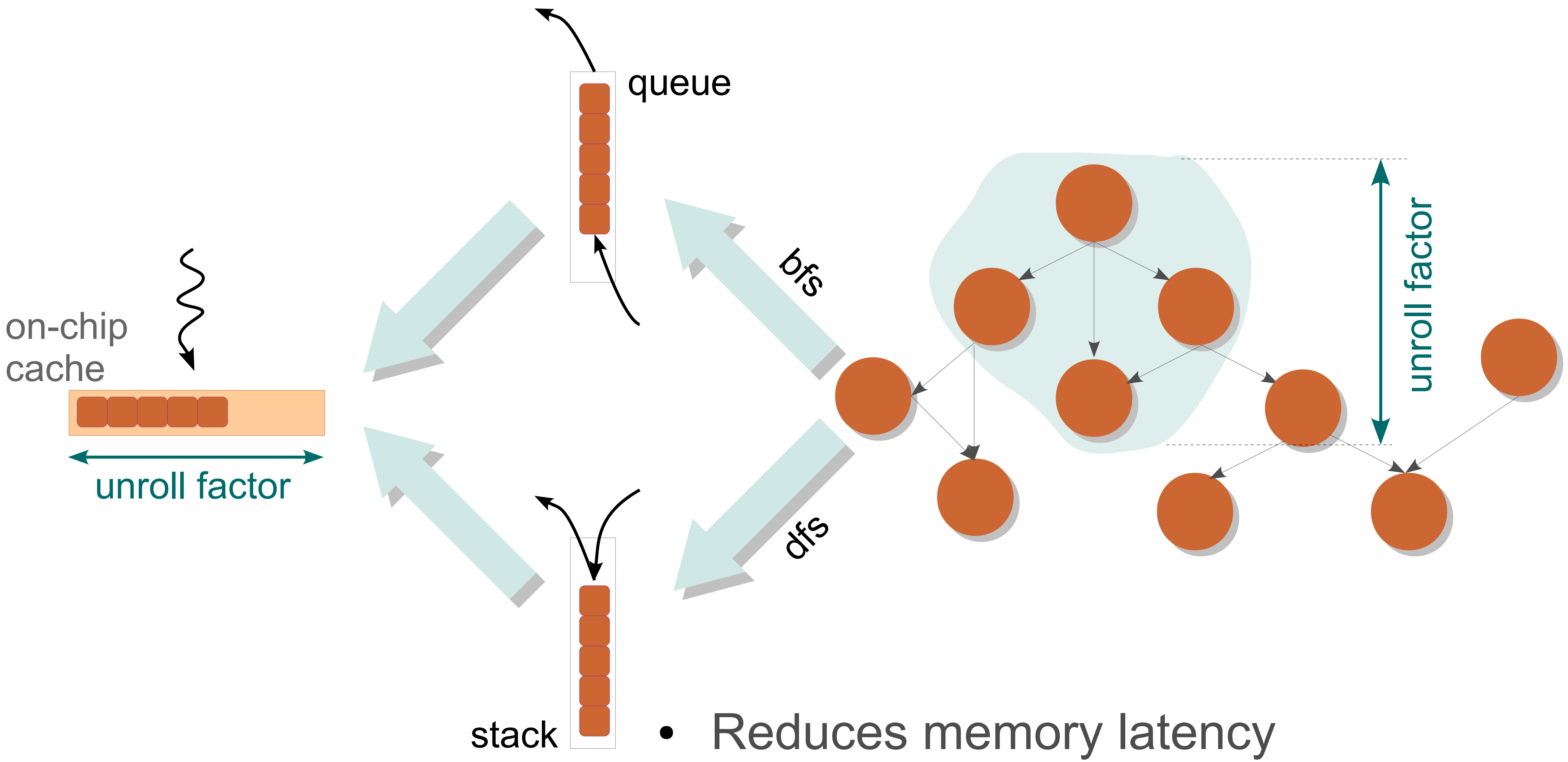
```
sssp_operator(src) {
    dsrc = distance[src]

    forall edges (src, dst, wt) {
        ddst = distance[dst]
        altdist = dsrc + wt

        if altdist < ddst
            distance[dst] = altdist
    }
}
```

Memory-bound kernel



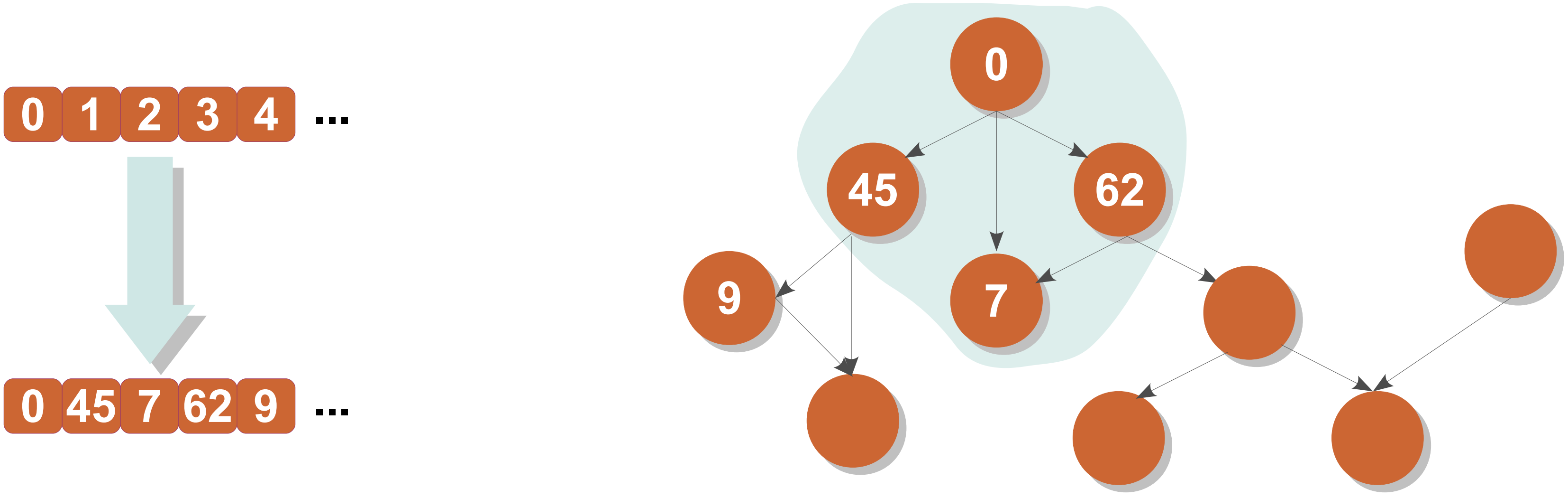
- Improves amount of computation per thread invocation
- Need to ensure absence of races
- Propagates information faster

Topology-driven: Exploiting Memory Hierarchy



- Reduces memory latency
- Requires careful selection of unroll factor

Topology-driven: Improved Memory Layout



- Bring logically close graph nodes also physically close in memory
- Improves spatial locality

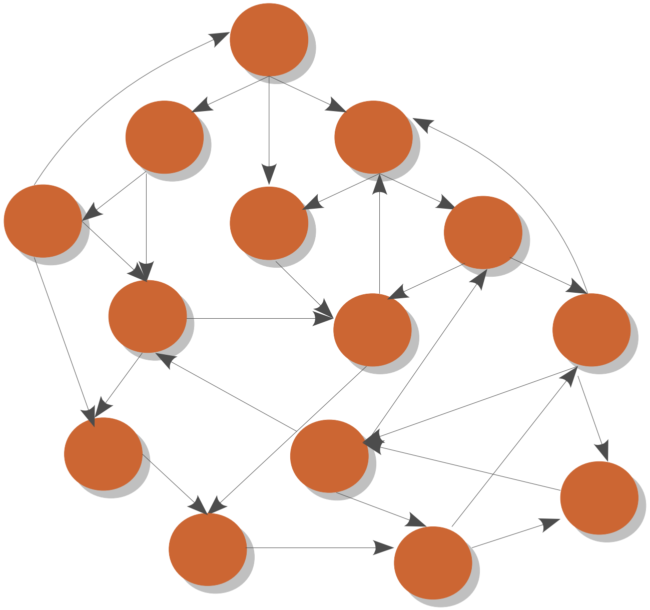
Outline

- Motivation
- Data-driven approach
- Topology-driven approach

➔ **Hybrid approach**

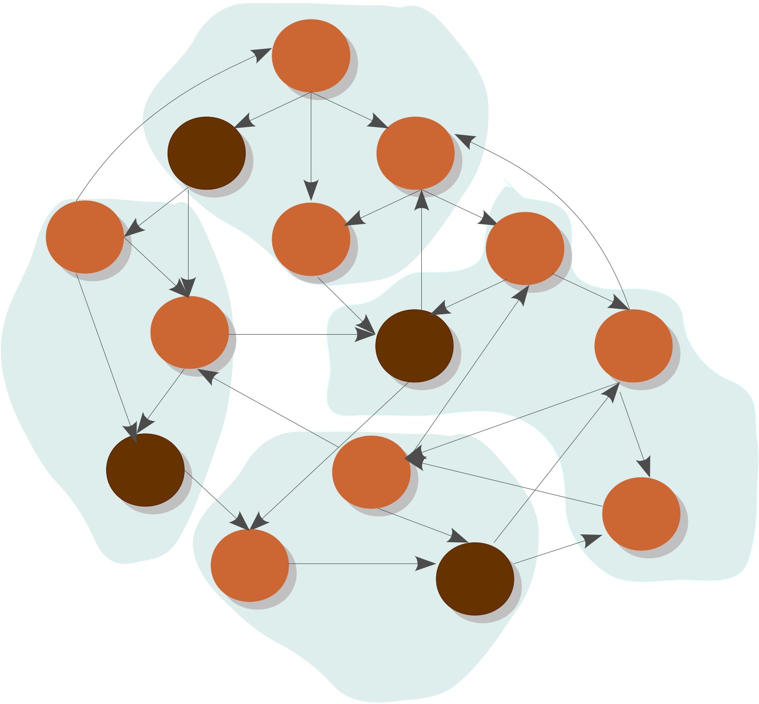
  - spatial
  - temporal
- Evaluation
- Conclusions

Spatial Hybrid

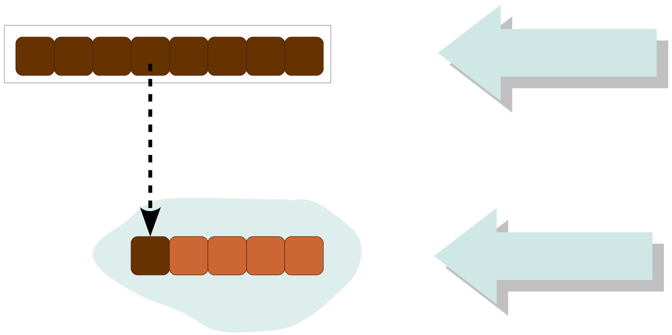


Shortest paths computation

Spatial Hybrid



Shortest paths computation



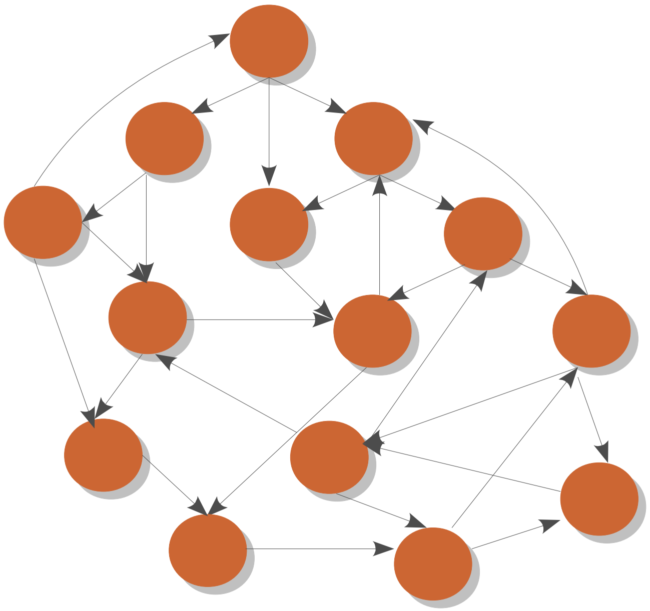
worklist

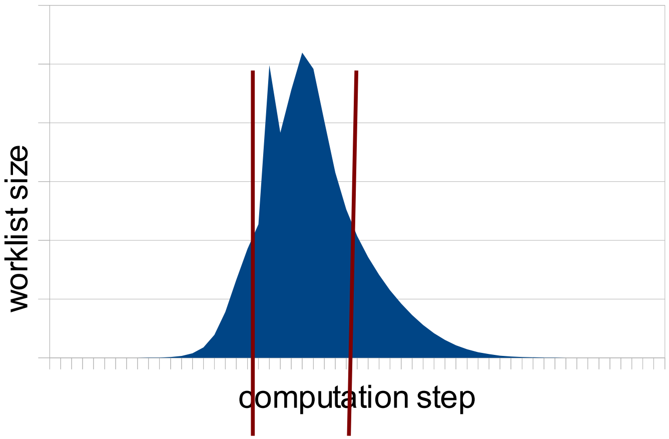
data-driven

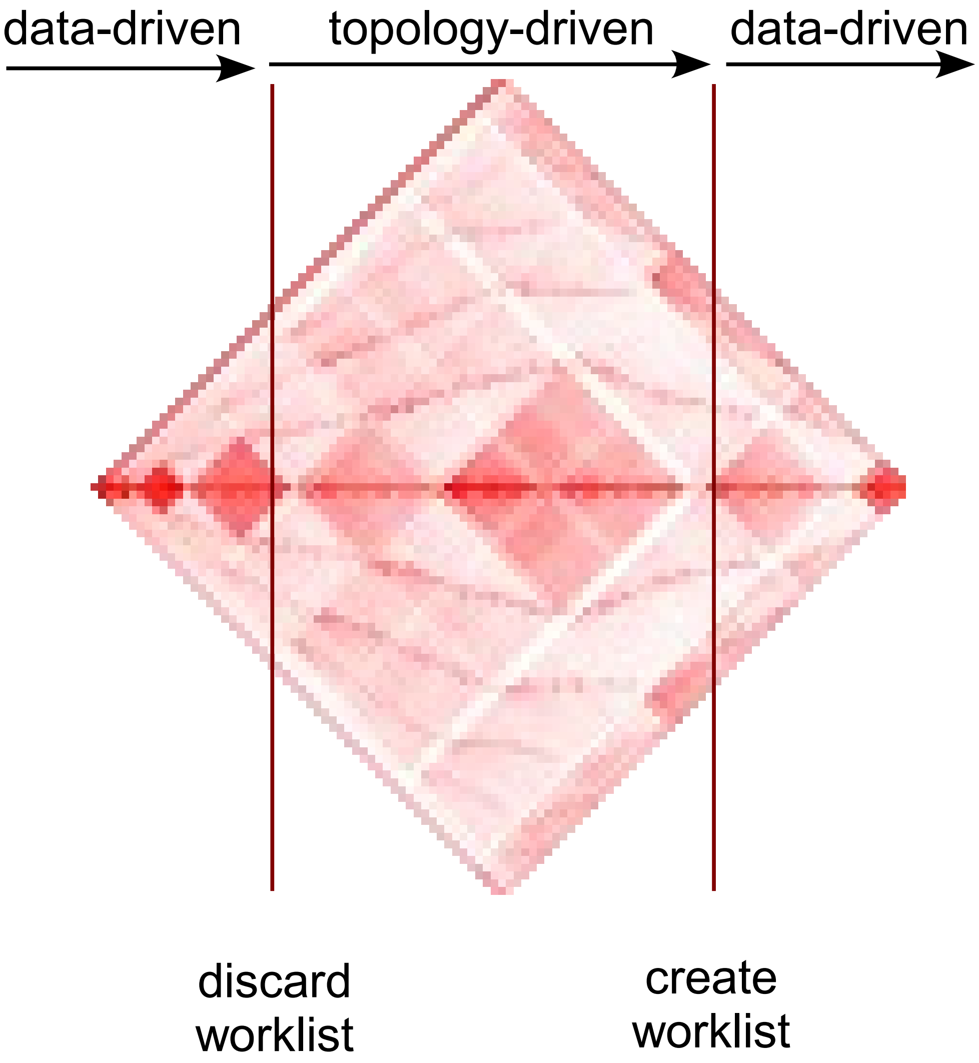
topology-driven

process all nodes in the partition

Temporal Hybrid







data-driven

topology-driven

data-driven

discard worklist

create worklist

Outline

- Motivation
- Data-driven approach
- Topology-driven approach
- Hybrid approach

➔ **Evaluation**

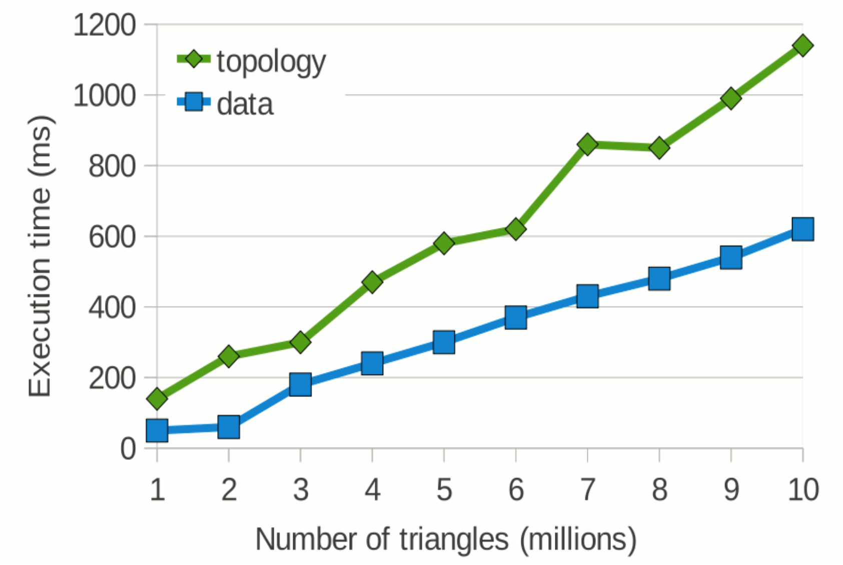
  - Fermi (Quadro 6000, 1.45 GHz, 448 cores over 14 SMs)
  - **LonestarGPU** benchmark suite

    http://iss.ices.utexas.edu/?p=projects/galois/lonestargpu

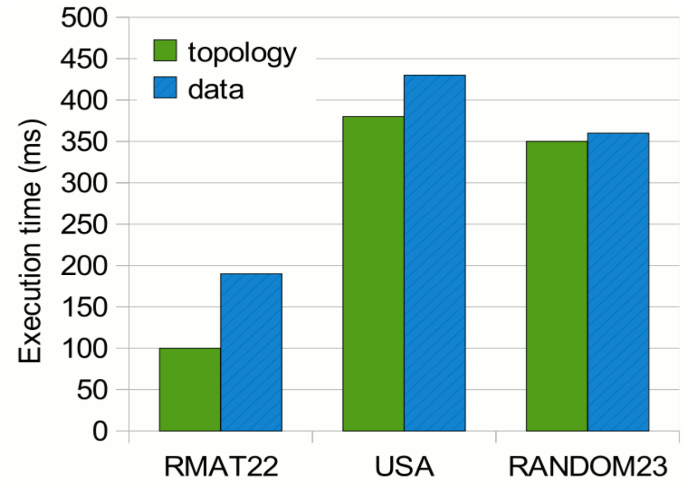
- Conclusions

Data-driven vs. Topology-driven

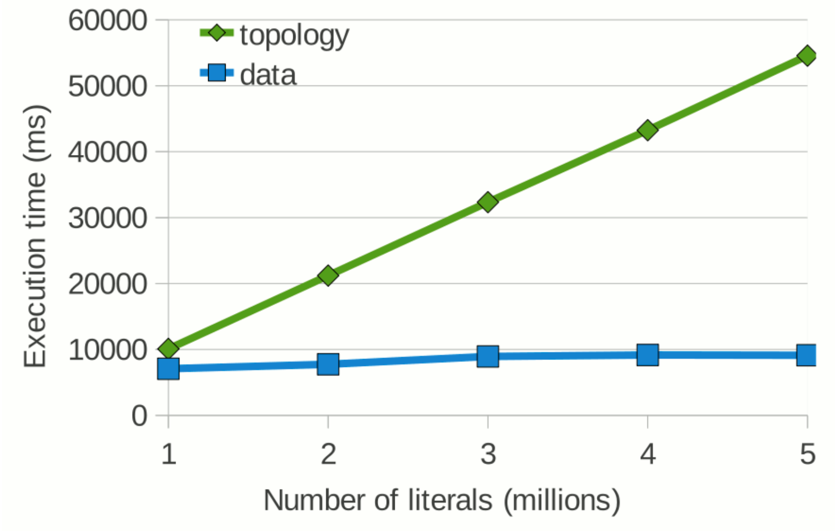
DMR



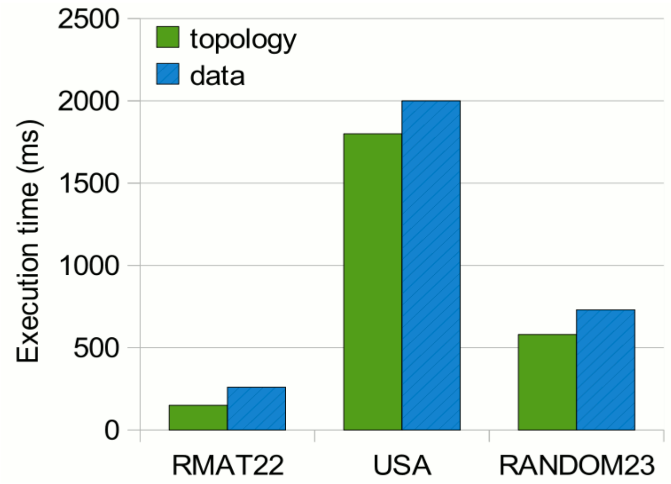
BFS



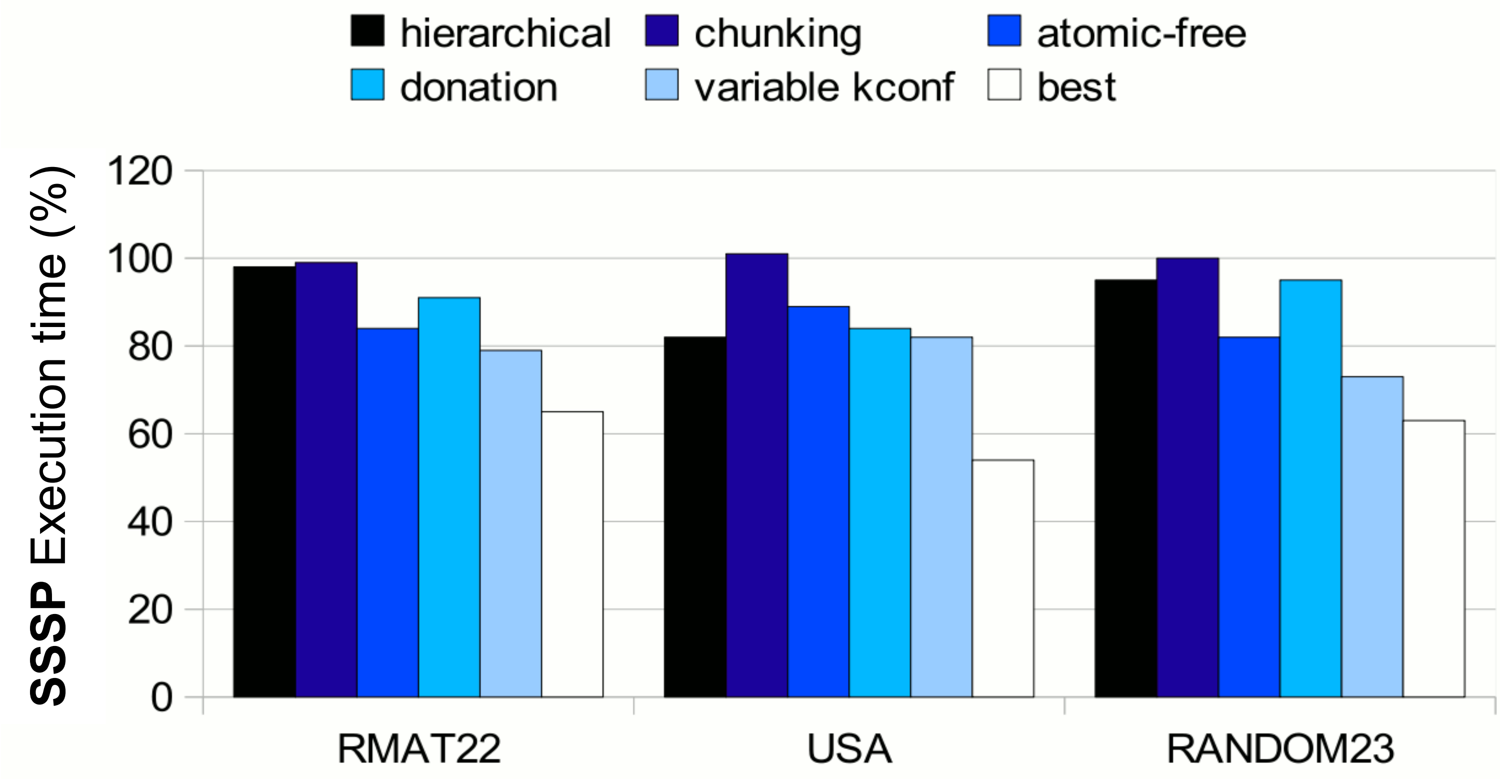
SP



SSSP

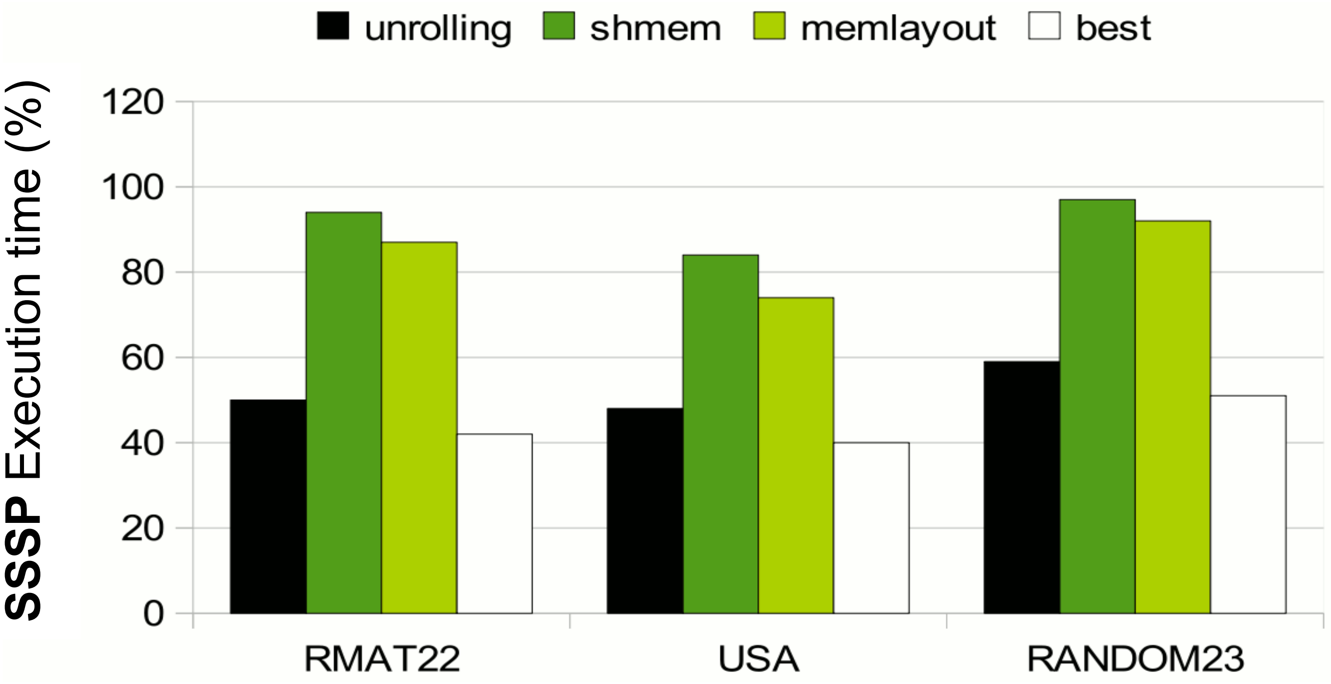


Data-driven Optimizations



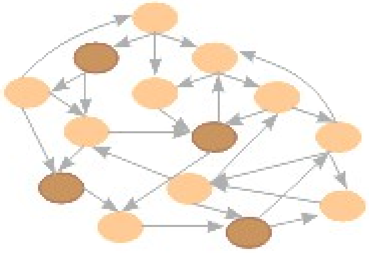
- Hierarchical worklists, atomic-free worklist update and varying configuration help
- Chunking is not effective
- Overall, performance improves by 40-50%

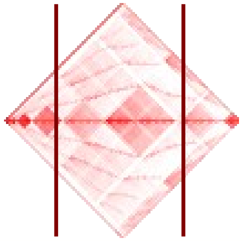
Topology-driven Optimizations

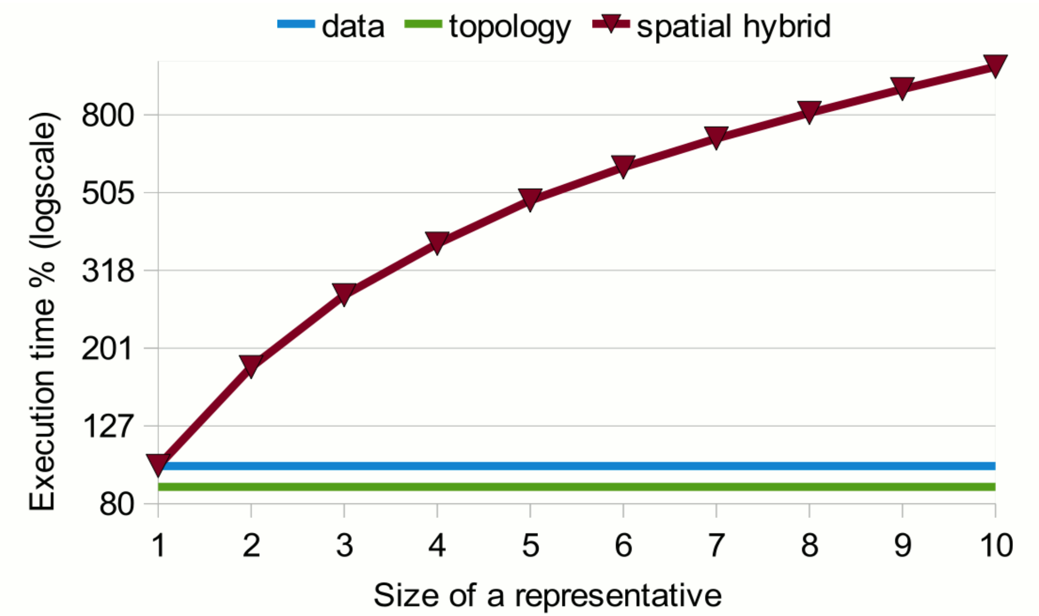


- Effect is more pronounced than the data-driven approach
- Unrolling helps the most
- Overall, performance improves by 50-60%

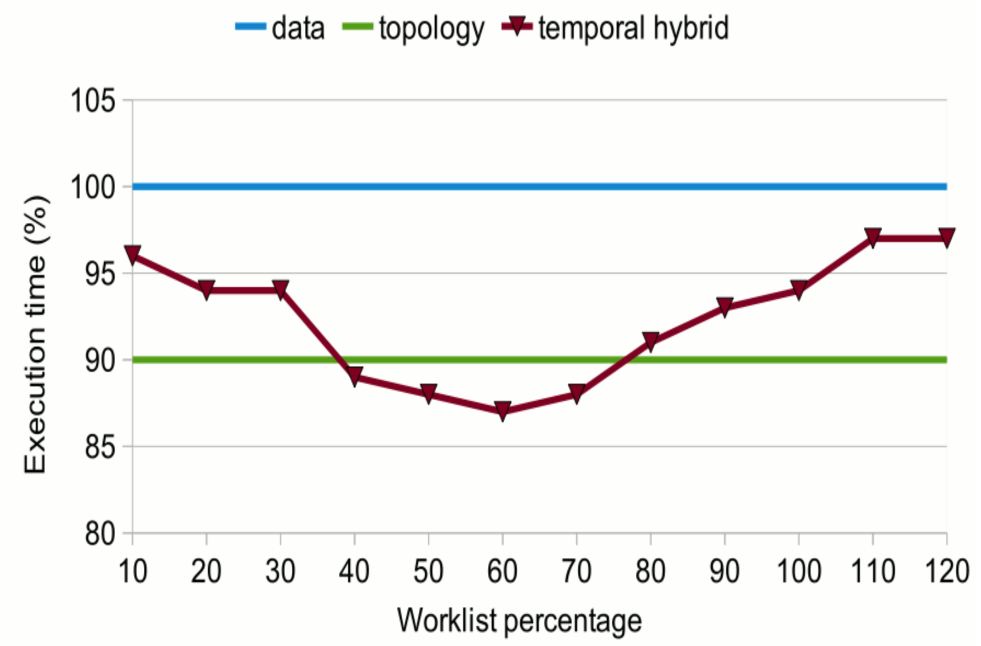
Spatial and Temporal Hybrid







SSSP

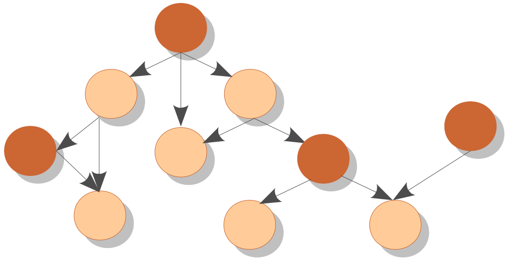


SSSP

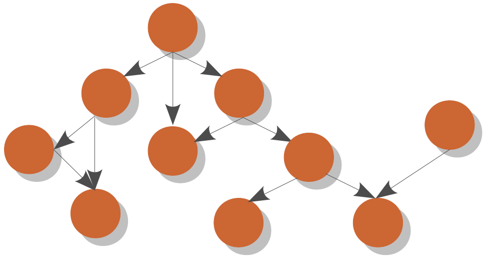
- Spatial hybrid has consistently reduced performance
- Temporal hybrid achieves performance better than the solo approaches

Conclusions

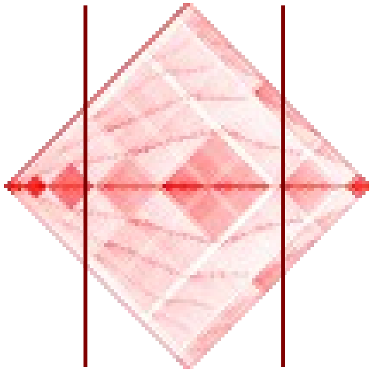
- Data-driven irregular computations usually perform better



- Topology-driven irregular computations perform better if additional algorithmic properties can be exploited



- Hybrid approaches may provide better performance than the individual approaches



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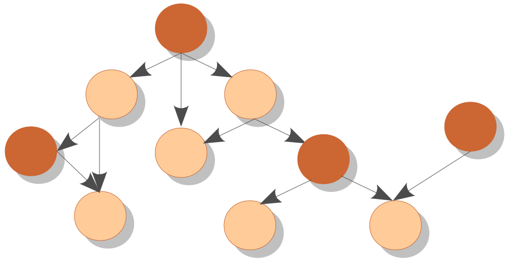

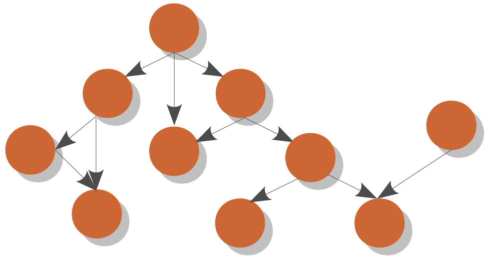

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Acknowledgments: Intel, NSF, NVIDIA, Qualcomm

LonestarGPU

ECL
Efficient Computing Laboratory

Galois

DMR Performance

SP Performance

BFS Performance

SSSP Performance