Resource Allocation for Multiple Concurrent In-network Stream-processing Applications

Anne Benoit Henri Casanova* Veronika Rehn-Sonigo
Yves Robert

LIP, École Normale Supérieure de Lyon
France

*University of Hawai'i at Manoa
USA

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Introduction and Motivation

Operator-mapping problem for in-network stream processing

- Applications structured as trees of operators
- Execution in steady-state
- Multiple data objects are continually updated at various locations on a network
- Multiple concurrent applications

Applications?

- Processing of data in a sensor network
- Video surveillance
- Continuous queries on distributed relational databases
- Network monitoring

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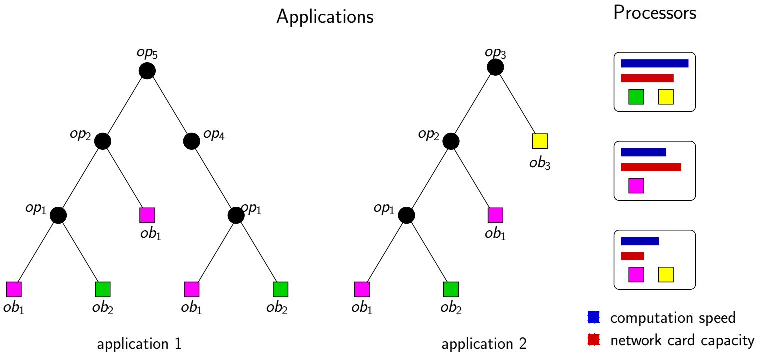
Rule of the Game



Goal

Minimize some cost function of the target platform while matching all application requirements.

Assess impact of reusing intermediate results.

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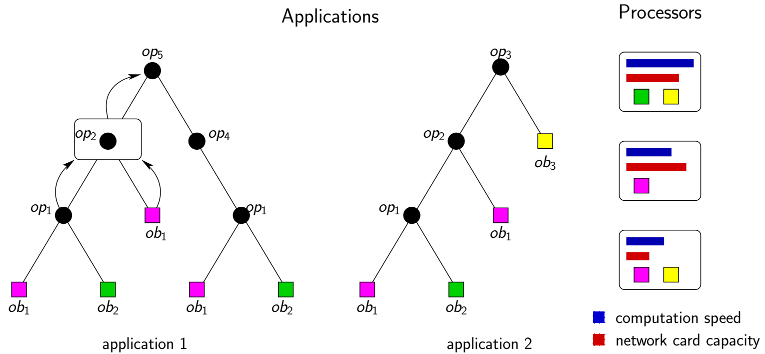

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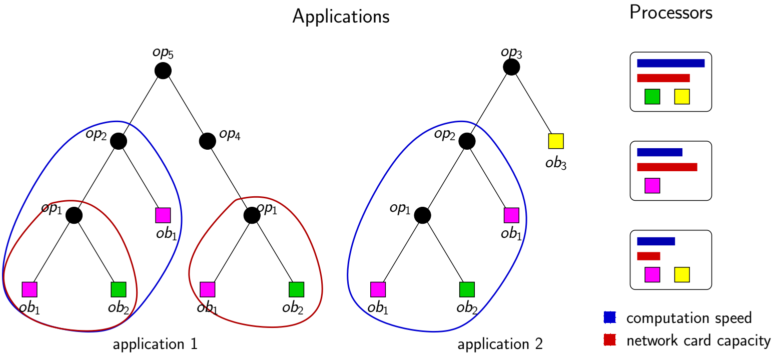

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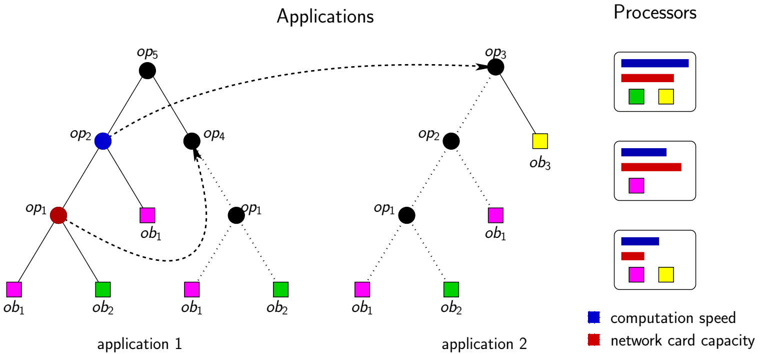

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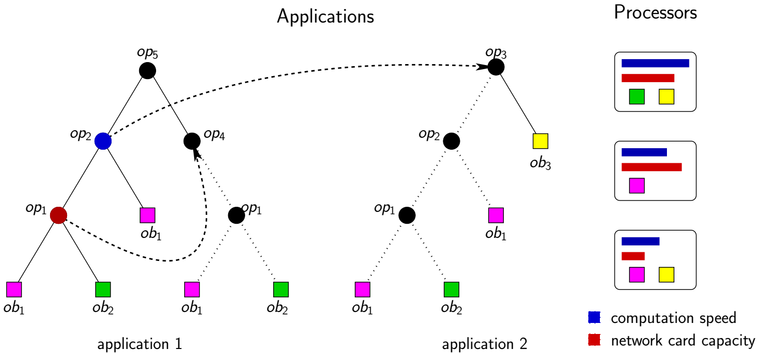

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Major Contributions

Theory
- Definition operator-placement problem
- Problem complexity
- Linear programming formulation

Practice
- Polynomial heuristics
- Experiments to compare heuristics and evaluate their performance

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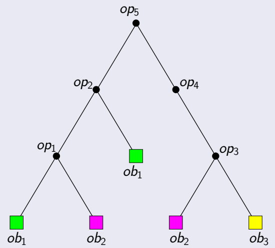
Outline of the Talk

The Application Model

- $\mathcal{K}$ applications
- $\mathcal{OP} = \{op_1, op_2, \dots\}$ set of operators
- $\mathcal{OB} = \{ob_1, ob_2, ob_3, \dots\}$ basic objects
- Computation of operator op_p: w_p operations, δ_p size of output

Application tree



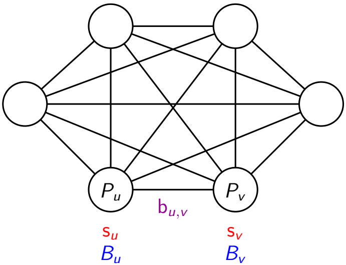
For application k:
$\rho^{(k)}$ application throughput

Object ob_j
- d_j size of ob_j
- $f_j^{(k)}$ download frequency
- $rate_j^{(k)} = d_j \times f_j^{(k)}$ bandwidth consumption

Platform and Communication Model

The platform

- $\mathcal{P}$ processors, fully connected graph (i.e., a clique)
- s_u: compute speed of proc. $P_u \in \mathcal{P}$
- B_u: network card capacity of $P_u \in \mathcal{P}$
- $b_{u,v} (= b_{v,u})$: bandwidth of bidirectional link between P_u and P_v



Communication Model

Full-overlap, bounded multi-port model: processor P_u can be involved in computing, sending data, and receiving data simultaneously.

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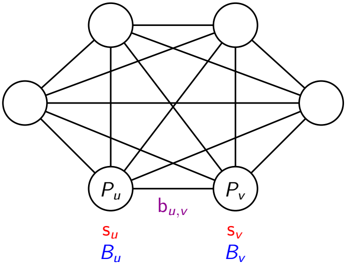

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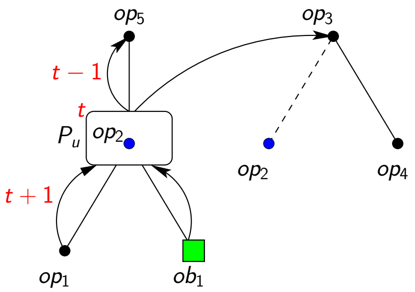
The Mapping Model

- Each processor is in charge of one or several tree nodes
- Node $n_i^{(k)}$ (op_p) mapped on processor P_u
- P_u computes t-th final result
- Sends to parent node(s) (if any) intermediate results for $(t-1)$-th final result
- Receives data from its non-leaf children (if any) for computing the $(t+1)$-th final result



Mapping Model

Constraints

- Application throughput $\rho^{(k)}$: $\forall P_u \in \mathcal{P}$,
$\sum_{p \in a_{op}(u)} \left(\max_{(k,i) \in \bar{a}(u) \mid op(n_i^{(k)}) = op_p} \left(\rho^{(k)}\right) \frac{w_p}{s_u} \right) \leq 1$
- Bandwidth capacity P_u: $\forall P_u \in \mathcal{P}$,
$\sum_{(j,v,k) \in Do(u)} rate_j^{(k)} + \sum_{P_v \in \mathcal{P}} \sum_{(j,u,k) \in Do(v)} rate_j^{(k)} + \sum_{(p,v,k) \in Ch(u)} \delta_p \rho^{(k)} + \sum_{(p,v,k) \in Par(u)} \delta_p \rho^{(k)} \leq B_u$
- Link bandwidth $P_u \longleftrightarrow P_v$: $\forall P_u, P_v \in \mathcal{P}$,
$\sum_{(j,v,k) \in Do(u)} rate_j^{(k)} + \sum_{(j,u,k) \in Do(v)} rate_j^{(k)} + \sum_{(p,v,k) \in Ch(u)} \delta_p \rho^{(k)} + \sum_{(p,v,k) \in Par(u)} \delta_p \rho^{(k)} \leq b_{u,v}$

Optimization Problems

Objective

Map operators onto processors such that a cost function is minimized and all application throughputs are achieved.

- **PROC-NB** minimizes the number of used processors;
- **PROC-POWER** minimizes the compute capacity and/or the network card capacity of used processors (e.g., a linear function of both criteria);
- **BW-SUM** minimizes the sum of the used bandwidth capacities;
- **BW-MAX** minimizes the maximum percentage of bandwidth used on all links.

Outline of the Talk

1. Framework
2. Complexity
3. Heuristics and Experiments
4. Conclusion

Complexity

All optimization problems are NP-hard.

- **PROC-NB** NP-complete in the strong sense even for a simple case: a HOM platform and a single application ($|\mathcal{K}| = 1$), that is structured as a left-deep tree, in which all operators take the same amount of time to compute and produce results of size 0, and in which all basic objects have the same size.
- **PROC-POWER** same proof as for PROC-NB.
- **BW-MAX** Reduction to 2-Partition: download objects with different rates on two processors for a single application.
- **BW-SUM** Reduction to Knapsack problem.

Integer Linear Programming

- Integer LP to solve the different optimization problems
- Many integer variables: no efficient algorithm to solve
- Approach limited to small problem instances

Outline of the Talk

Overview of Heuristics (1)

Heuristics for the PROC-POWER problem, considering the compute capacities of used processors.

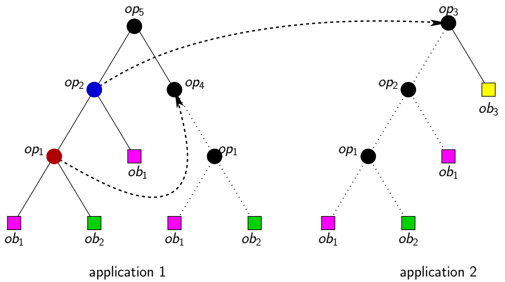
Server selection strategies:

- (S1) Select the fastest processor (blocking);
- (S2) Select the processor with the fastest network card (blocking);
- (S3) Select the fastest processor (non-blocking);
- (S4) Select the processor with the fastest network card (non-blocking).

Overview of Heuristics (2)

Heuristics: Reuse of intermediate results

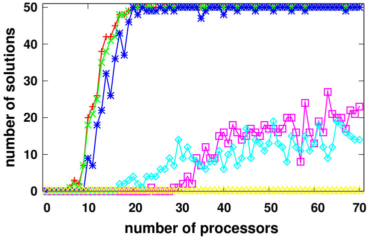
(H1) RandomNoReuse
(H2) Random
(H3) TopDownBFS
(H4) TopDownDFS
(H5) BottomUpBFS
(H6) BottomUpDFS



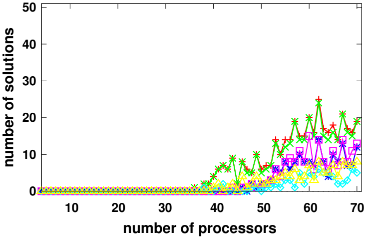
Results

Number of processors increases.
50 runs. 5 applications. 50 operators.

Successful runs.



(S3) Fastest proc.



(S3) Fastest proc - no reuse.

Results

Number of processors increases.
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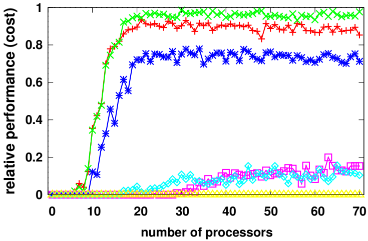
Relative performance.



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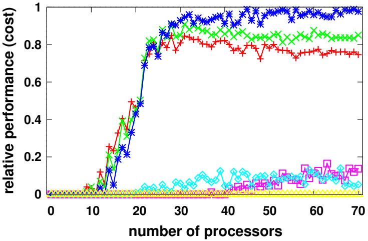
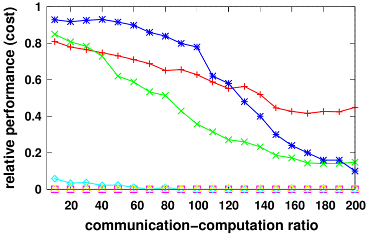


(S1) Fastest proc - blocking.

Results

Communication-computation ratio increases.
50 runs. 5 applications. 50 operators.

Relative performance.



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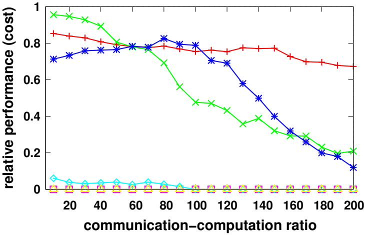

(S2) Fastest netw. card - block.

Summary

- Random approach dramatically bad
- Neglecting reuse limits success rate and quality of solution in terms of cost
- Top Down approach turns out to be the best
- BottomUp only with BFS competitive
- DFS unable to reuse results efficiently (bandwidth)
- Strong dependency of processor selection strategy on solution quality
- Solid combination: TopDownBFS with fastest proc - non-blocking

Outline of the Talk

Related Work

Babu et al., Liu et al.

Execution of continuous queries on data streams

Chen et al., van Rennesse et al.

In-network stream processing systems
These systems all face the same question: where should operators be mapped in the network?

Pietzuch et al., Srivastava et al.

Operator-mapping problem for in-network stream processing

Conclusion

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- Multiple concurrent applications
- Reuse of intermediate results
- Formulation of different operator-placement problems
- Complexity analysis: NP-completeness for all optimization problems
- Integer linear programming formulation

Practical side

- Polynomial time heuristics
- Simulation: TopDownBFS with fastest proc - non blocking

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Perspectives

- Heuristics for the other optimization problems: PROC-NB, BW-SUM, BW-MAX
- More general cost function $w_{i,u}$ (time required to compute operator i onto processor u) $\longrightarrow$ more heterogeneity
- Mutable applications: Operators can be rearranged based on operator associativity and commutativity rules

  Ex: relational database applications