Bandwidth-Aware Page Placement in NUMA Systems

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Page placement in Non-Uniform Memory Access (NUMA)

• NUMA emerging as the norm in high-end servers

• In a NUMA system, the access bandwidth/latency depends on where the data resides

Page placement problem in NUMA:
Where should the OS map the data pages of an application to optimize its performance?
“Uniform-workers” Placement Strategy

However, this strategy fails to maximize memory throughput in modern asymmetric NUMA systems by considerable margins:

- Distributes pages evenly, even though the BWs are asymmetric
- Does not use the available BW of the other nodes

Two scenarios where application’s threads are clustered on a subset of nodes (worker nodes):
- When the application is deployed in a given node partition of a co-scheduled system
- When the application does not scale beyond a subset of the available cores

If the application is bandwidth(BW)-intensive, uniform-workers is better than “first-touch”
- Therefore, it is used in most SoTA schemes
BWAP: Bandwidth-Aware Page Placement

• **Goal:** Devise and enforce an efficient interleaving of the application’s pages across NUMA nodes

• **Main focus:**
  - Bandwidth-intensive applications
  - Running in a subset of nodes of a larger NUMA system
    - co-scheduled scenario
    - scenario where applications do not scale
Key insights of BWAP

1. To maximize bandwidth, consider placing the application’s pages on every node
   • Including nodes where the application is not running

2. To take bandwidth asymmetry into account, use weighted interleaving
   • Assign different weights to different nodes
   • Each node’s weight denotes the fraction of pages that will be mapped to that node

3. Choose weights according to the architecture and the application, by combining:
   • Analytical performance model of the target NUMA architecture (canonical tuner)
   • Incremental page migration for application-specific tuning (DWP tuner)
Canonical Tuner

- Agnostic of the target application, runs offline
- Models the memory bandwidth of the NUMA topology
- Calculates the optimal weight distribution that maximizes the performance of a reference bandwidth-intensive application
- Output: **canonical weight distribution**

Data-to-Worker Proximity (DWP) Tuner

- Canonical weight distributions may not be suited for target application
- DWP tuner converts the canonical weight distribution to one that is optimized for the target application
- Finds an appropriate **data-to-worker proximity** factor (DWP)
  - DWP determines how many pages will be assigned to the set of worker nodes
  - Achieves this through an incremental page migration mechanism
Evaluation

• Compare BWAP with state-of-the-art page placement policies
  • Linux default policy (first-touch)
  • Uniform-workers (uniform interleaving across workers)
  • Uniform-all (uniform interleaving across all nodes)
  • AutoNUMA
  • BWAP-uniform (variant of BWAP, which disables the canonical tuner)

• Benchmarks: multithreaded benchmarks from PARSEC, SPLASH, NAS
• Machines: 2 NUMA systems
  • AMD Opteron Processor, 8 NUMA nodes
  • Intel Xeon CPU E5-2660 v4, 4 NUMA nodes
• Execution scenarios: co-scheduled and stand-alone
Co-scheduled Scenario
(1 worker node, 8-node machine)

- Best performing solutions are those that fully exploit the available memory BW by placing pages across all nodes, i.e., uniform-all and BWAP.
- BWAP is able to outperform both uniform-workers and autonuma by up to 1.66x, and uniform-all by up to 1.50x.
Stand-alone scenario (8-node machine)

- First-touch is usually the worst alternative for multi-worker scenarios
- Benefits of BWAP over the uniform interleaving alternatives drop when more workers are involved
- As applications use an increasingly larger worker node set:
  - The worker vs. non-worker dichotomy fades away.
  - The inter-worker canonical weight distributions tend to uniformity
Conclusions

• Today’s usual techniques for page placement still rely on the obsolete assumption of a symmetric architecture

• We propose BWAP, a novel approach for asymmetric BW-aware placement of pages in NUMA systems

• BWAP improves the gains of state-of-the-art policies by up to 66%, on commodity NUMA machines

• BWAP is available at https://github.com/gureya/bwap

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