Leveraging MPST in Linux with Application Guidance to Achieve Power and Performance Goals

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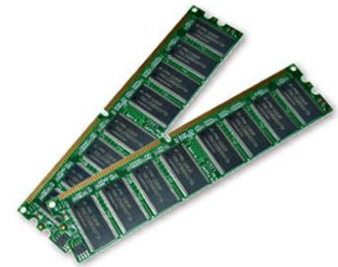
Introduction



- Memory has become a significant player in power and performance
- Memory power management is challenging
- Propose a collaborative approach between applications, operating system, and hardware:
  - Applications – insert instructions to communicate to OS memory usage intent
  - OS – re-architect memory management to interpret application intent and manage memory over hardware units
  - Hardware – communicate hardware layout to the OS to guide memory management decisions
- Implemented framework by re-architecting recent Linux kernel
- Experimental evaluation with industrial-grade JVM

Why 

- CPU and Memory are most significant players for power and performance
  - In servers, memory power == 40% of total power [1]

- Applications can direct CPU usage
  - threads may be affinitized to individual cores or migrated b/w cores
  - prioritize threads for task deadlines (with nice)
  - individual cores may be turned off when unused

- ***Surprisingly, much of this flexibility does not exist for controlling memory***

Example Scenario

- System with database workload with 512GB DRAM
  - All memory in use, but only 2% of pages are accessed frequently
  - CPU utilization is low
- **How to reduce power consumption?**

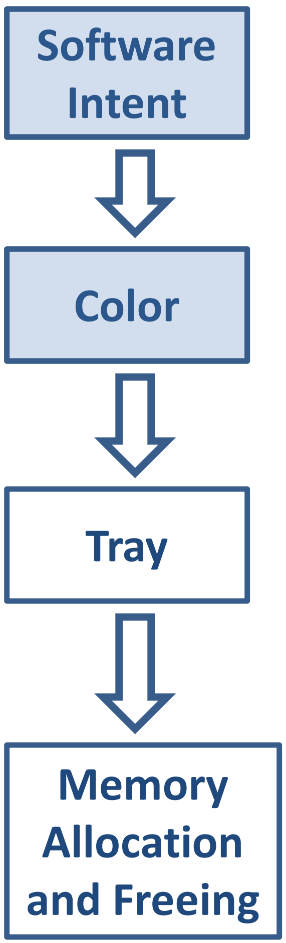
Challenges in Managing Memory Power

- Memory refs. have temporal and spatial variation
- At least two levels of virtualization:
  - Virtual memory abstracts away application-level info
  - Physical memory viewed as single, contiguous array of storage
- No way for agents to cooperate with the OS and with each other
- Lack of a tuning methodology

A Collaborative Approach

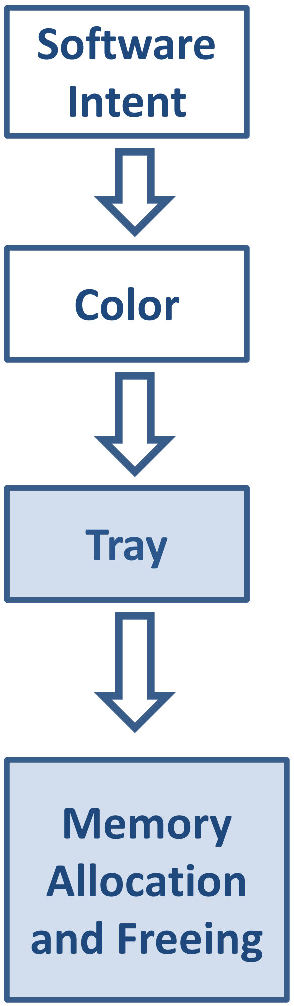
- Our approach: enable applications to guide mem. mgmt.
- Requires collaboration between the application, OS, and hardware:
  - Interface for communicating application intent to OS
  - Ability to keep track of which memory hardware units host which physical pages during memory mgmt.
- To achieve this, we propose the following abstractions:
  - Colors
  - Trays

Communicating Application Intent with Colors



- Color = a hint for how pages will be used
  - Colors applied to sets of virtual pages that are alike
  - Attributes associated with each color
- Attributes express different types of distinctions:
  - Hot and cold pages (frequency of access)
  - Pages belonging to data structures with different usage patterns
- Allow applications to remain agnostic to lower level details of mem. mgmt.

Power-Manageable Units Represented as Trays



- Tray = software structure containing sets of pages that constitute a power-manageable unit
- Requires mapping from physical addresses to power-manageable units
- ACPI 5.0 *memory power state table* (MPST):
  - Phys. address ranges --> mem. hardware units

Coloring Example

- Application with two distinct sets of memory
  – Large set of infrequently accessed (cold) memory
  – Small set of frequently accessed (hot) memory
- Specify guidance as a set of standard intents
  – MEM-INTENSITY (hot or cold)
  – MEM-CAPACITY (% of dynamic RSS)
- Intents enable OS to manage mem. more efficiently
  – Save power by co-locating hot / cold memory
  – Recycle large span of cold pages more aggressively

Configuration File to Specify Intents

```
# Specification for frequency of reference:
INTENT    MEM-INTENSITY

# Specification for containing total spread:
INTENT    MEM-CAPACITY

# Mapping to a set of colors:
MEM-INTENSITY    RED     0 // hot pages
MEM-CAPACITY     RED     5 // hint - 5% of RSS
MEM-INTENSITY    BLUE    1 // cold pages
MEM-CAPACITY     BLUE    3 // hint - 3% of RSS
```

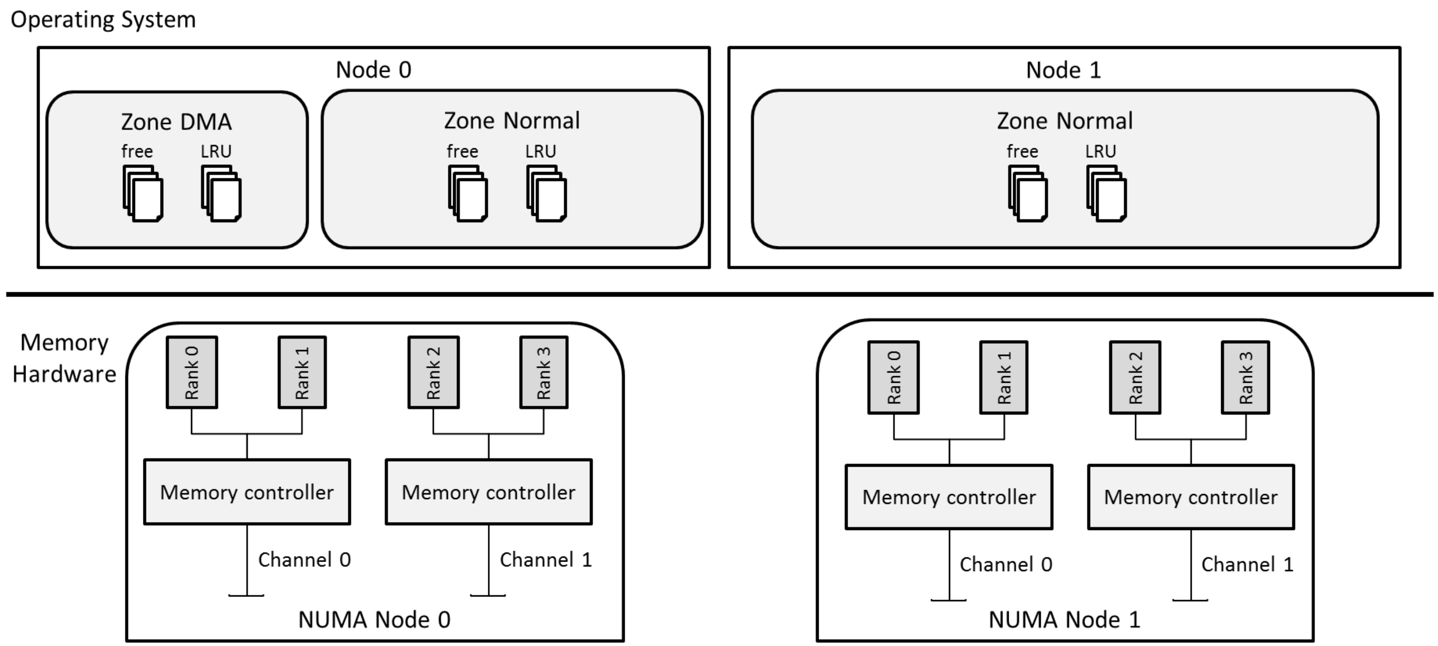
- Associate colors with intents in configuration files
- Parses config file to create and structure data passed to the OS

Memory Coloring System Calls

System Call	Arguments	Description
mcolor	addr, size, color	Applies *color* to a virtual address range of length *size* starting at *addr*
get_addr_mcolor	addr, *color	Returns the current color of the virtual address *addr*
set_mcolor_attr	color, *attr	Associates the attribute pointed to by *attr* with *color*
get_mcolor_attr	color, *attr	Returns the attribute currently associated with *color*

- Specify colors / intents using system calls
- Use *mcolor*, *set_mcolor_attr* to color application pages

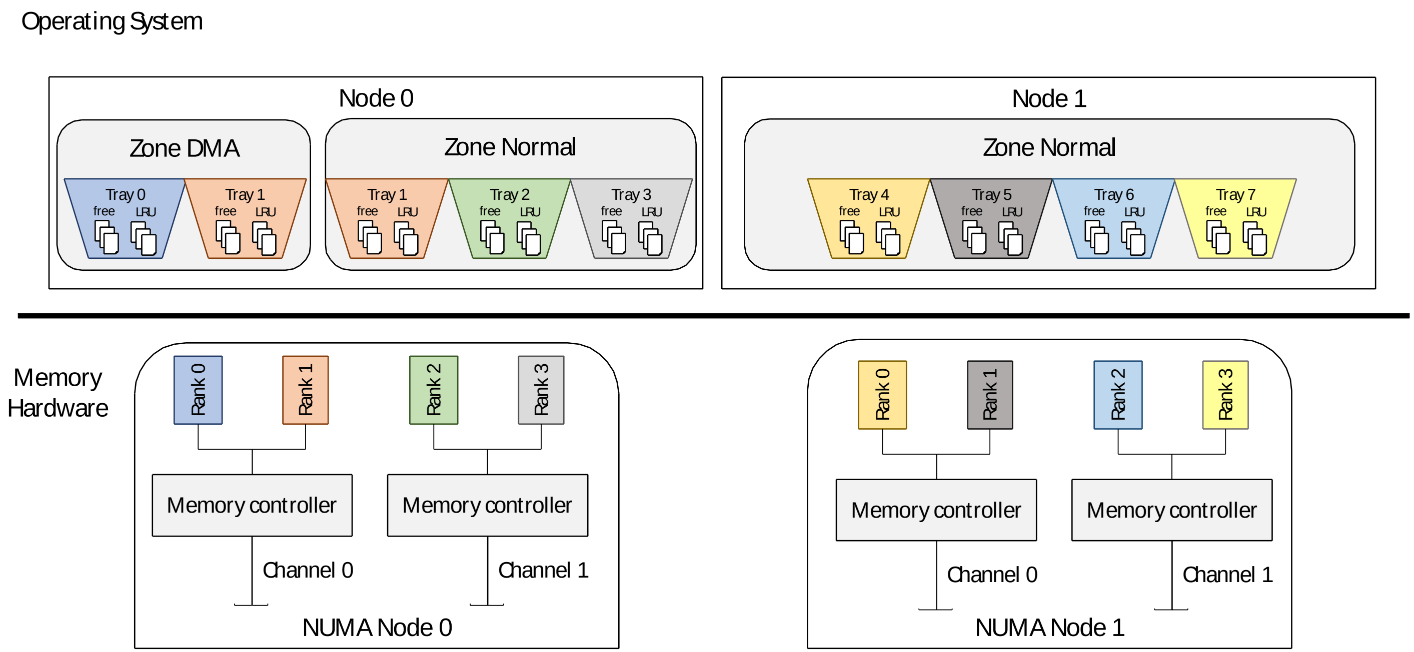
Memory Management in Linux



Memory management in the default Linux kernel

- Default Linux kernel organizes physical memory *hierarchically*
  - Nodes --> zones --> lists of physical pages (free lists, LRU lists)
- Distinction for pages on different nodes, but not different ranks

Tray Implementation



Memory management with tray structures in our modified Linux kernel

- Trays exist as a division between zones and physical pages
- Each tray corresponds to a rank, maintains its own lists of pages
- Kernel memory mgmt. routines modified to operate over trays

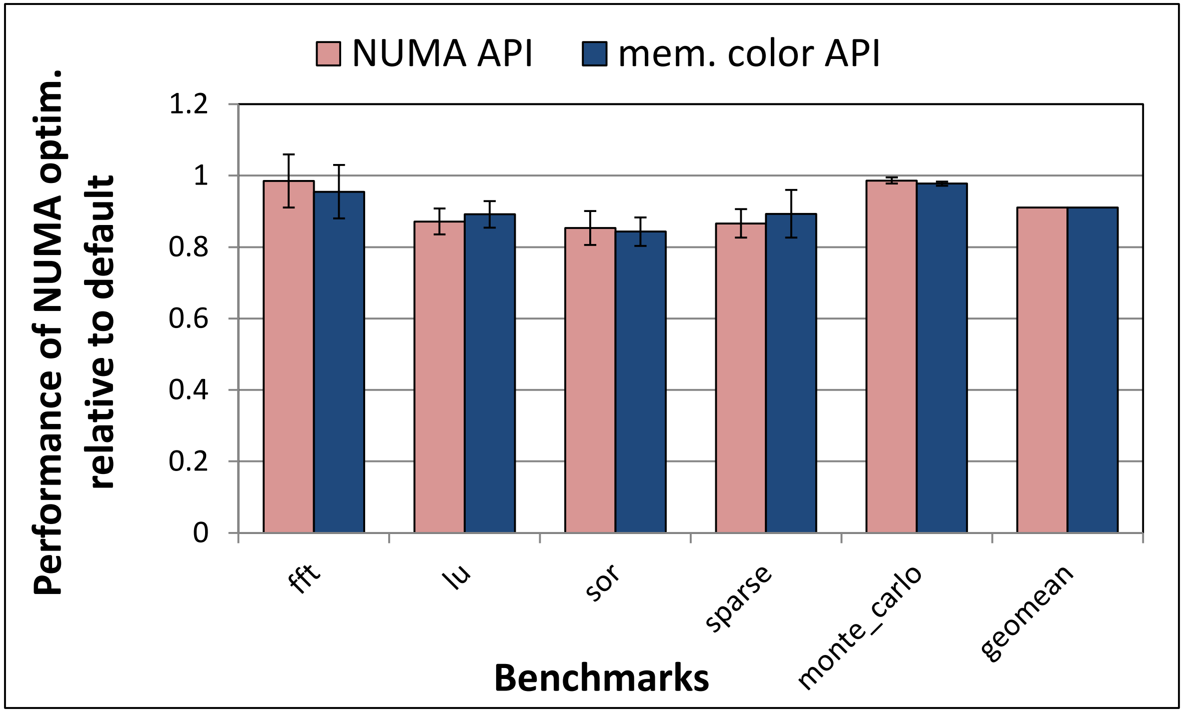
Evaluation

- Emulating NUMA API’s
- Enabling power consumption proportional to the active footprint

Emulating NUMA API's

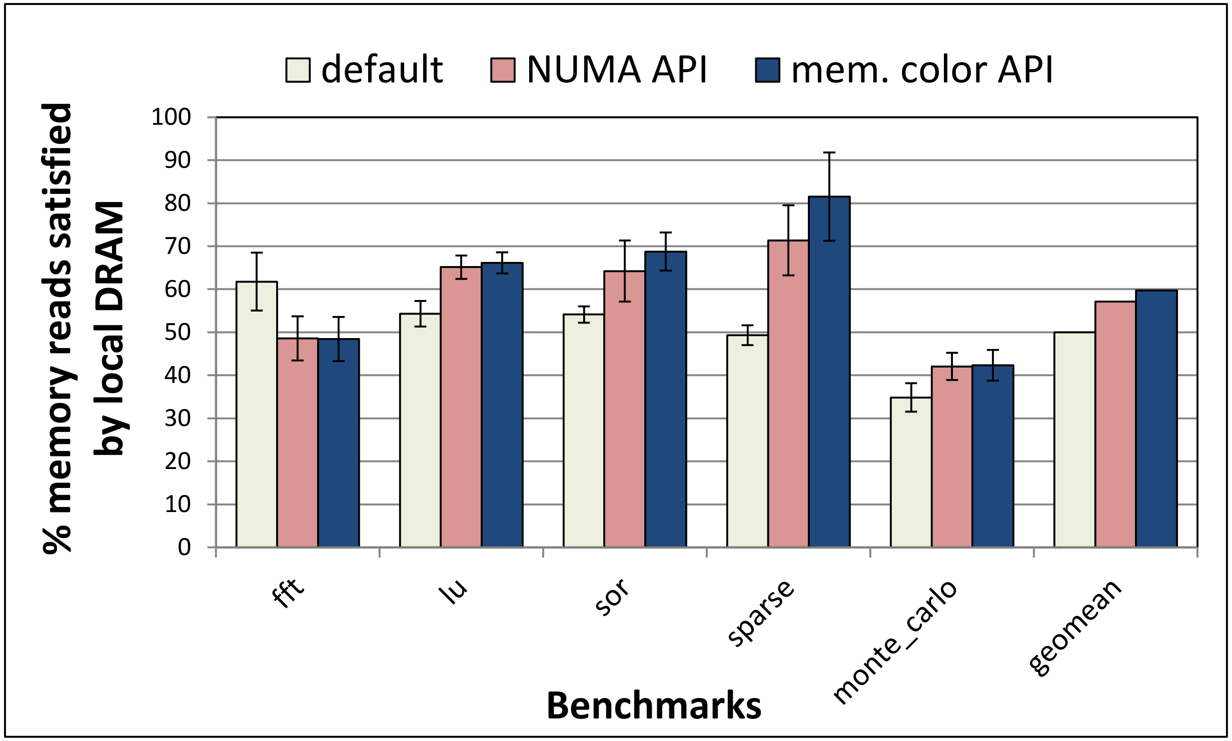
- Modern server systems include API for managing memory over NUMA nodes
- Our goal: demonstrate that framework is flexible and efficient enough to emulate NUMA API functionality
- Experimental Setup
  - Oracle's HotSpot JVM includes optimization to improve DRAM access locality (implemented w/ NUMA API's)
  - Modified HotSpot to control memory placement using mem. coloring
  - Compare performance with the default configuration and with optimization implemented w/ NUMA API's and w/ memory coloring

Memory Coloring Emulates the NUMA API



- Performance of SciMark 2.0 benchmarks with "NUMA-optimized" HotSpot implemented with (1) NUMA API's and (2) memory coloring framework
- Performance is similar for both implementations

Memory Coloring Emulates the NUMA API

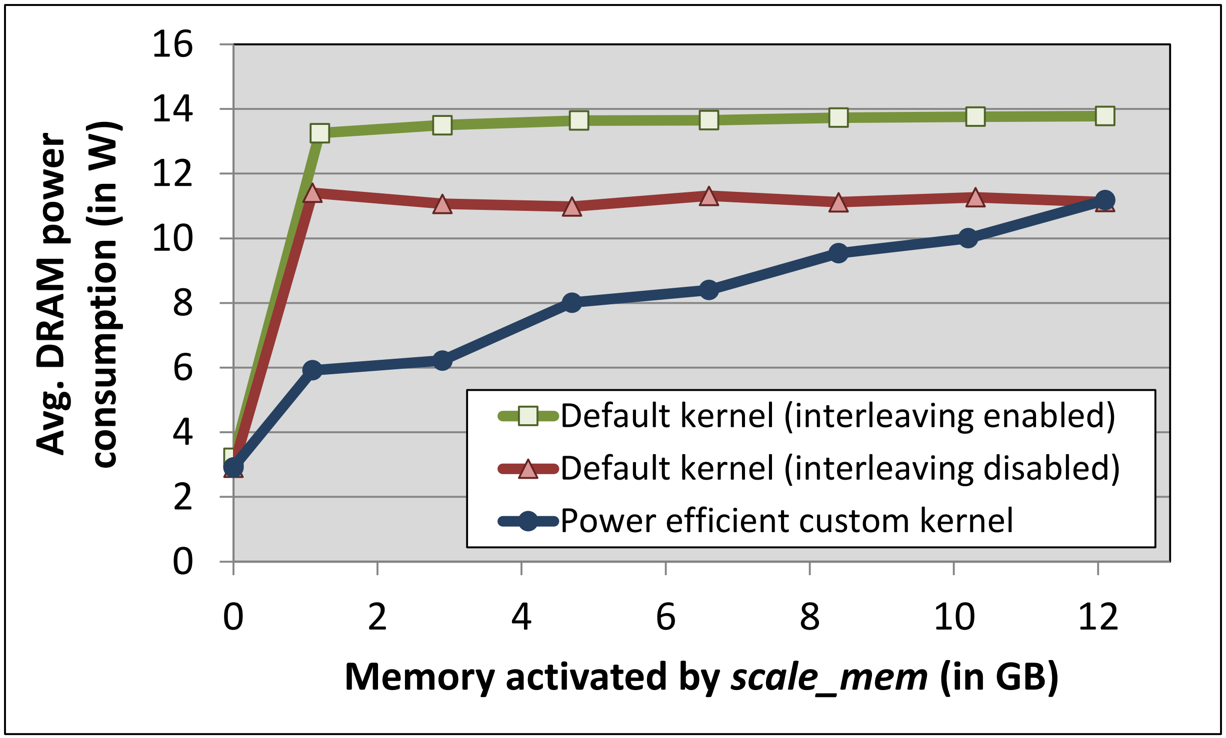


- % of memory reads satisfied by NUMA-local DRAM for SciMark 2.0 benchmarks with each HotSpot configuration.
- Performance with each implementation is (again) roughly the same

Enabling Power Consumption Proportional to the Active Footprint

- Our goal: demonstrate potential of our custom kernel to reduce power in memory
- Experimental setup:
  - Custom workload that incrementally increases memory usage in 2GB steps
  - Compare three configurations on single node of server machine with 16GB of RAM
    - Default kernel with physical address interleaving
    - Default kernel with no interleaving
    - Custom kernel with tray-based allocation

Enabling Power Consumption Proportional to the Active Footprint



- Default kernel yields high power consumption even with small footprint
- Custom kernel – tray-based allocation enables power consumption proportional to the active footprint

Future Improvements

- Problems:
  - Little understanding of which colors or coloring hints will be most useful for existing workloads
  - All colors and hints must be manually inserted
- Developing a set of tools to profile, analyze and control memory usage for applications
- Capabilities we are working on:
  - Detailed memory usage feedback over colored regions
  - On-line techniques to adapt guidance to feedback
  - Compiler / runtime integration to *automatically* partition and color address space based on profiles of memory usage activity

Conclusion

- A critical first step in meeting the need for a fine-grained, power-aware flexible provisioning of memory.
- Initial implementation demonstrates value
  - But there is much more to be done
- Questions?

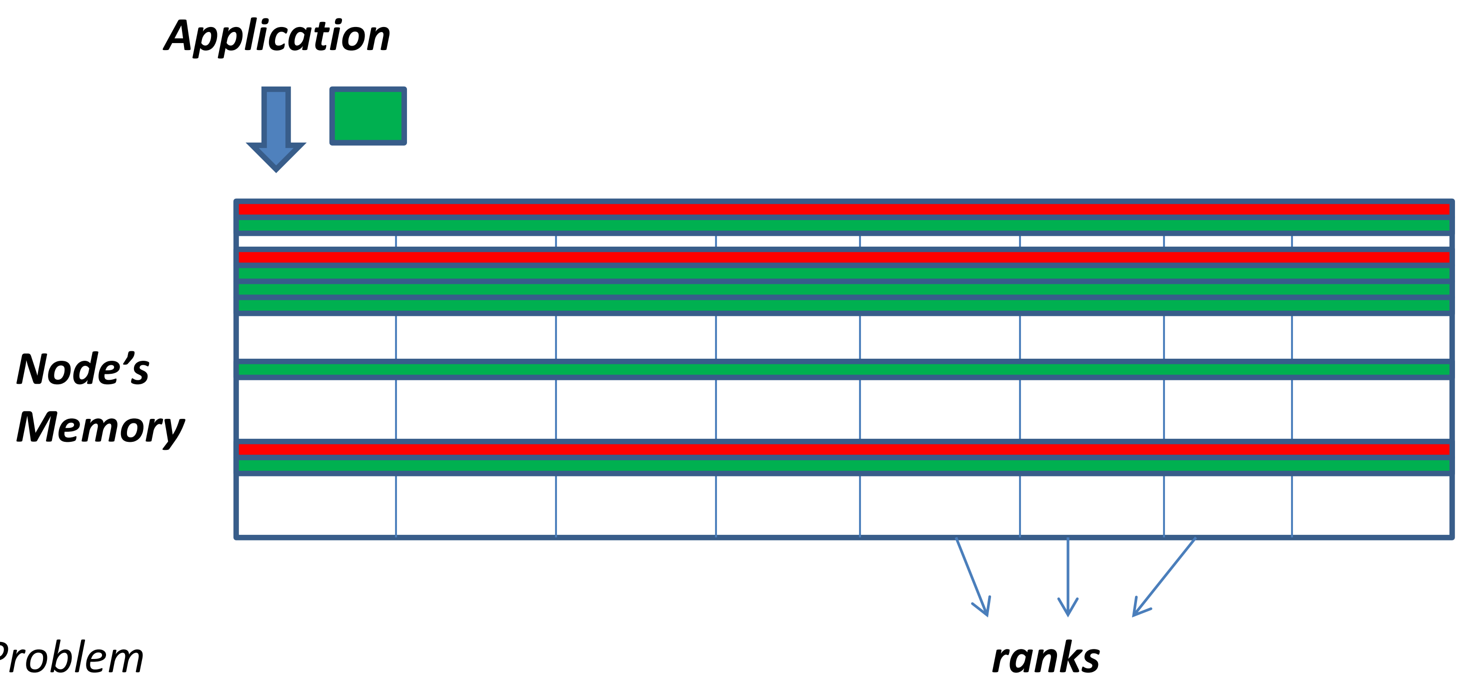
References

1. C. Lefurgy, K. Rajamani, F. Rawson, W. Felter, M. Kistler, and T. W. Keller. Energy management for commercial servers. Computer ,36 (12):39–48, Dec. 2003

Backup

Default Linux Kernel

Pages of different types — ***Frequently referenced*** — ***Infrequently referenced***

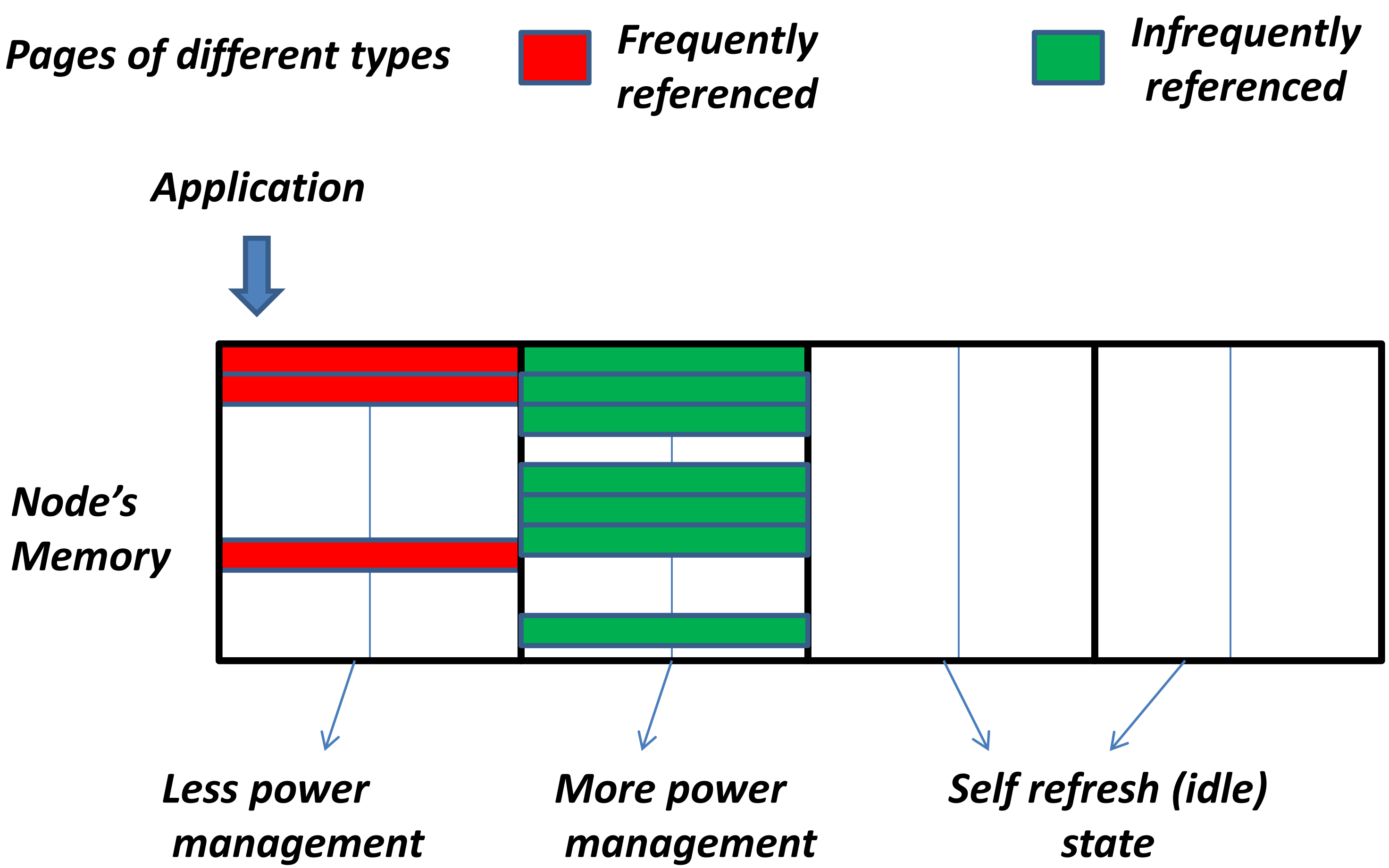


Problem

Operating system does not see a distinction between:

- ***different types of pages*** *from the application*
- ***different units of memory*** *that can be independently power managed*

Custom Kernel with Memory Containerization



Note: not drawn to scale- 10^6 4kB pages can be contained in a 4GB DIMM

Analysis to Automatically Generate Memory Coloring Hints

- Advantages to memory coloring:
  - Broad spectrum of hints can be overlapped
  - Hints can adapt to changes in the system
- Specific tasks
  - Build post-processing to search profiling data for regions to color
  - Construct analysis to relate objects that should be colored to source code
  - Manually insert coloring hints into application to apply ideal guidance and evaluate its impact

Novel System Tools

- Memory usage statistics over colored regions
  - Similar to `/proc` tools that enable users to query system-wide or per-application memory usage
  - Example: monitor page faults over a particular data structure
  - Will further improve memory usage guidance
- Monitoring memory usage over trays
  - Benefits applications such as whole-system virtualization
  - Provide user-level access to trays through `/proc`

More Workloads and Usage Scenarios

- Evaluate approach with complex, multi-tier workloads at the realistic scale of server systems
  – Potential applications: open source database, web server, J2EE software packages
- Explore maximizing performance by distributing high-value data widely across memory channels
- Hints for expected access patterns
  – Application guided read ahead or fault ahead with structures with expected sequential access
- Different page recycling policies for trays