The Virtual Block Interface: A Flexible Alternative to the Conventional Virtual Memory Framework

SAFARI

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Full Paper
https://people.inf.ethz.ch/omutlu/pub/VBI-virtual-block-interface_isca20.pdf

Full Talk Video
https://www.youtube.com/watch?v=7c6LgVrCwPo

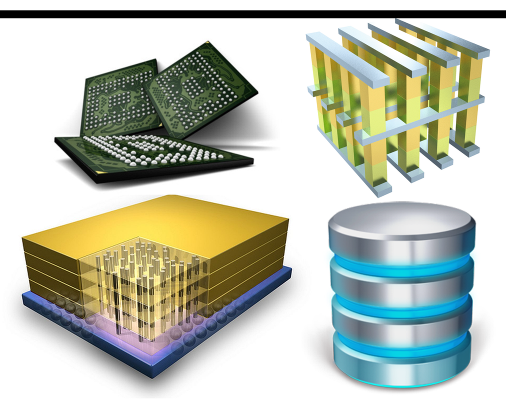
1: Motivation

Applications

Cannot adapt efficiently

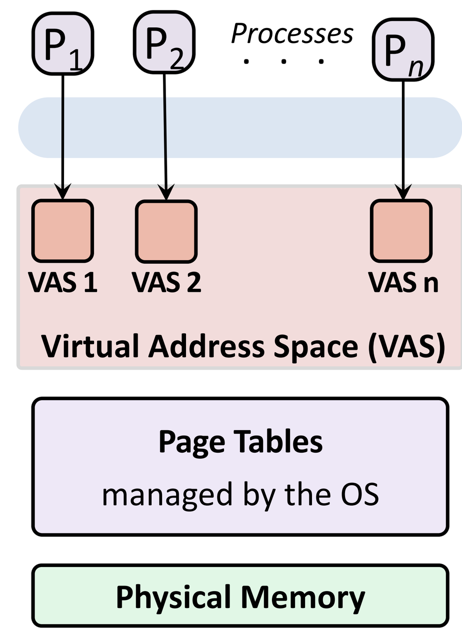
Virtual Memory
managed by the operating system

Hardware

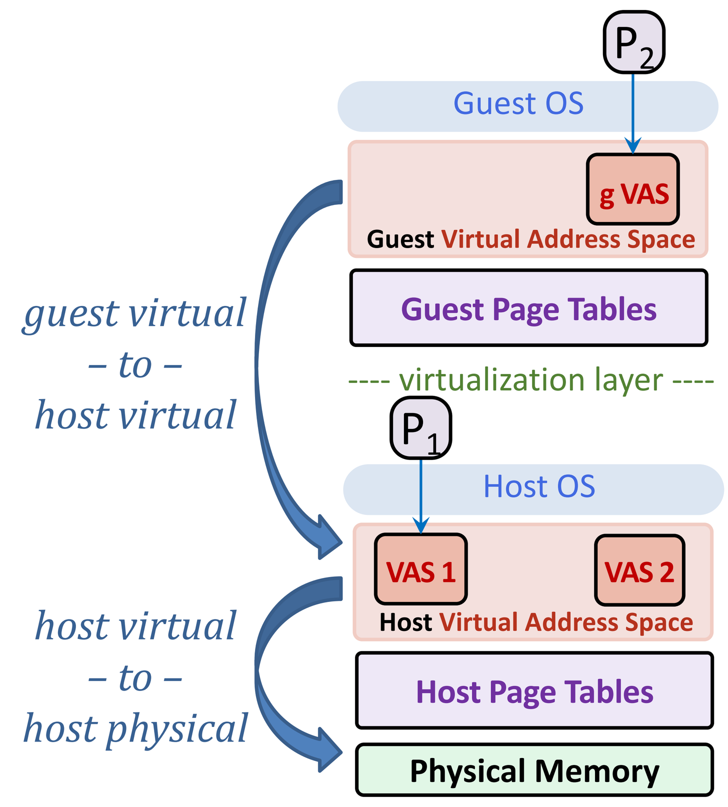


- **Modern computing systems continue to diversify** with respect to system architecture, memory technologies, and applications' memory needs
- **Continually adapting the conventional virtual memory** framework to each possible system configuration is **challenging**

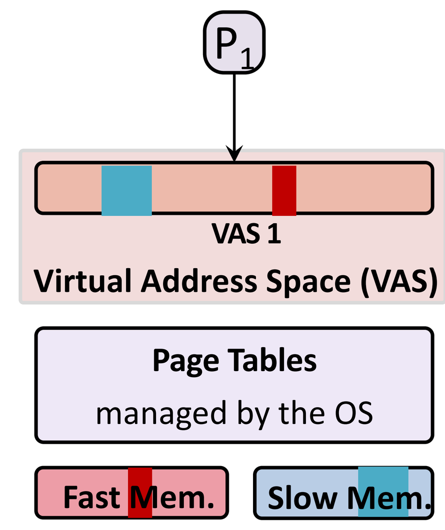
2: Example Challenges of the Conventional Virtual Memory Framework



1. **Page tables need to be shared between, and understood by both the hardware and the OS, resulting in rigid page table structures**
   - Challenging to implement the page table flexibility that applications can benefit from



2. **In virtual machines, both the guest and host OS perform address translation, resulting in an extra level of indirection**
   - Challenging to perform computation in virtualized environments, efficiently



3. **OS that defines and manages the address mapping, has low visibility into fine-grained runtime memory behavior information**
   - Challenging in heterogenous memories to make timely migration decisions based on quickly changing memory access patterns or other dynamic behavior

3: Our Goal

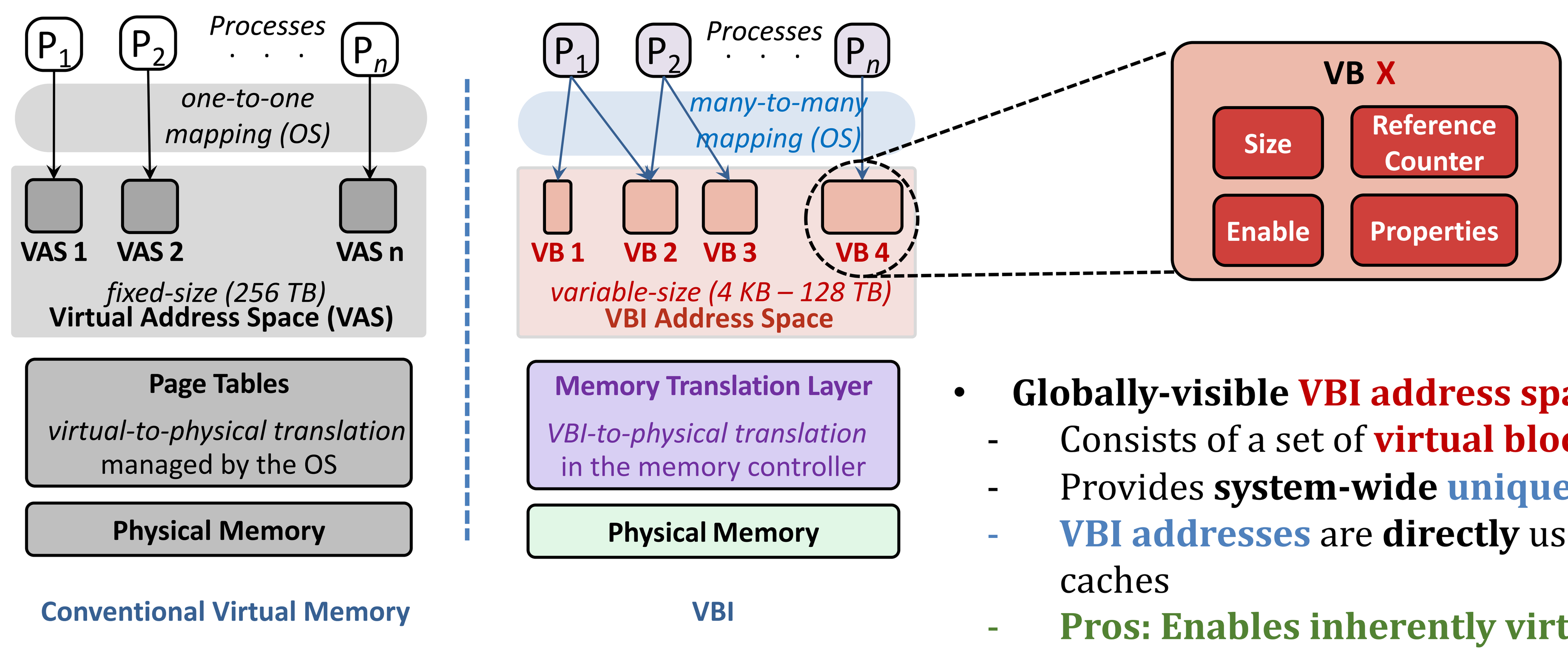
Design an alternative virtual memory framework that
- **Efficiently and flexibly supports increasingly diverse system configurations**
- **Provides the key features of conventional virtual memory framework while eliminating its key inefficiencies**

4: Virtual Block Interface (VBI)

Key idea:
Delegate physical memory management to dedicated hardware in the memory controller

Guiding Principles:
1. **Size virtual address spaces appropriately for processes**
   - Mitigates translation overheads of unnecessarily large address spaces
2. **Decouple address translation from access protection**
   - Defers address translation until necessary to access memory
   - Enables the flexibility of managing translation and protection using separate structures
3. **Communicate data semantics to the hardware**
   - Enables intelligent resource management

5: VBI Design Overview



Achieving the guiding principles:
1. **A process' VBs define its address space**, i.e., determined by the **actual needs of the process**
2. **Address mapping** is dedicated to the **MTL**, while **OS** retains full control over **managing the access permissions**
3. **Each VB is associated** with a set of information:
   - A System-wide unique ID
   - Size of the VB
   - Enable bit
   - Reference counter: number of processes attached to the VB
   - Properties bit vector: semantic information about VB contents, such as access pattern, latency sensitive vs. bandwidth sensitive

- **Globally-visible VBI address space**
  - Consists of a set of **virtual blocks** (VBs) of different sizes
  - Provides **system-wide unique VBI addresses**
  - **VBI addresses** are **directly** used to access on-chip caches
  - **Pros: Enables inherently virtual caches**
- **All VBs are visible to all processes**
  - **OS** controls which processes access which VBs
  - Each process has **its own permissions** (read/write/execute) when **attaching** to a VB
  - OS maintains a list of **VBs attached to each process** used to perform permission checks
- **Processes map each semantically meaningful unit of information to a separate VB**
  - e.g., a data structure, a shared library
- **Memory management is delegated to the Memory Translation Layer (MTL) in the memory controller**
  - Address translation and Physical memory allocation
  - Translation structures are **not shared** with the OS
  - **Per-VB translation structure** tuned to the VB's characteristics
  - **Pros: many benefits, including**
    - **Address translation overhead** for the processes running inside a **virtual machine**, is **no different** than the processes running **natively on system**
    - Enabling **flexible translation structures**

6: Optimizations Enabled by VBI

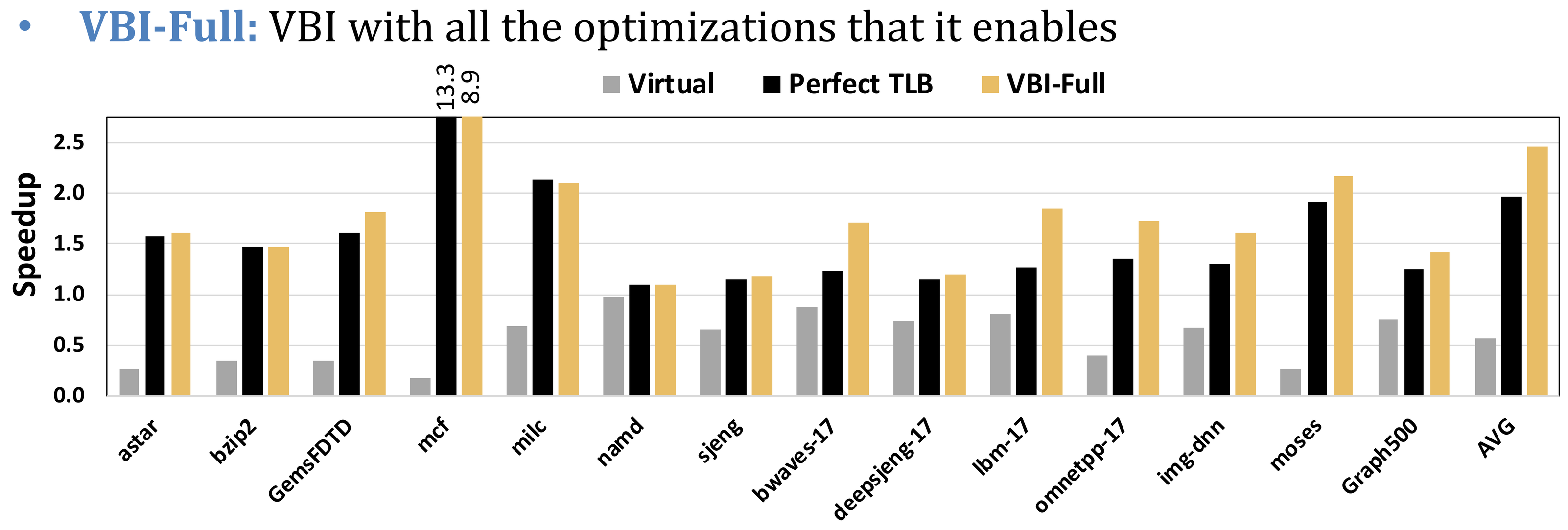
Naturally enabled by VBI and not easily attainable before:

Inherent to VBI design
- Appropriately sized process address space
- Flexible address translation structures
- Communicating data semantics to the hardware
- Inherently virtual caches
- Eliminating 2D page walks in virtual machines

Covered in the paper
- Delayed physical memory allocation
- Early memory reservation mechanism

7: Example Use Case: Address Translation

- **Native:** applications run natively on an x86-64 system
- **Virtual:** applications run inside a virtual machine (accelerated using 2D page walk cache [Bhargava+, ASPLOS'08])
- **Perfect TLB:** an unrealistic version of Native with no translation overhead
- **VBI-Full:** VBI with all the optimizations that it enables



Key Takeaways

1. **VBI-full** improves the performance, by 2.4X on average compared to **Native**
2. **VBI-full** enables **significant performance improvement** in virtualized environments (4.3X on average compared to **Virtual**)
3. **VBI-full** outperforms **Perfect TLB** (by 49% on average) as the **optimizations that VBI enables are not limited to only reducing the address translation overhead**

8: Conclusion

VBI is a promising new virtual memory framework
- **Can enable several important optimizations**
- **Increases design flexibility for virtual memory**
- **A new direction for future work in novel virtual memory frameworks**