Exploring the Design Space of Combining Linux with Lightweight Kernels for Extreme Scale Computing

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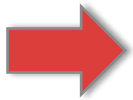
Outline

- **Motivation**
- **Background**
  - HPC OS Architecture and Lightweight kernels (LWK)
- **Linux + LWK**
  - Issues and Requirements
  - Design
    - Proxy model
    - Direct model
- **Comparison**
- **Evaluation**
- **Conclusion**

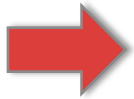
Motivation

- **Complexity of high-end HPC systems keeps growing**
  - Extreme degree of parallelism
  - Heterogeneous core architectures
  - Deep memory hierarchy
  - Power constrains



Need for scalable, reliable performance and capability to rapidly adapt to new HW

- **Applications have also become complex**
  - In-situ analysis, workflows
  - Sophisticated monitoring and tools support, etc..
  - Isolated, consistent simulation performance

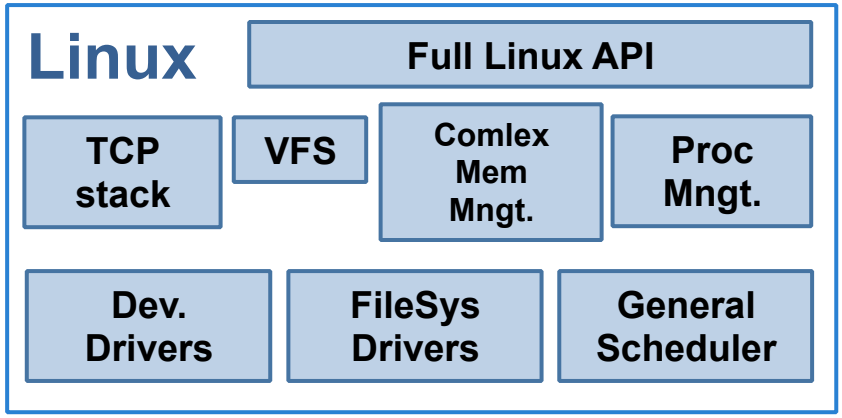


Dependence on POSIX and the rich Linux APIs

- **Seemingly contradictory requirements..**
- **Is the current system software stack ready for this?**

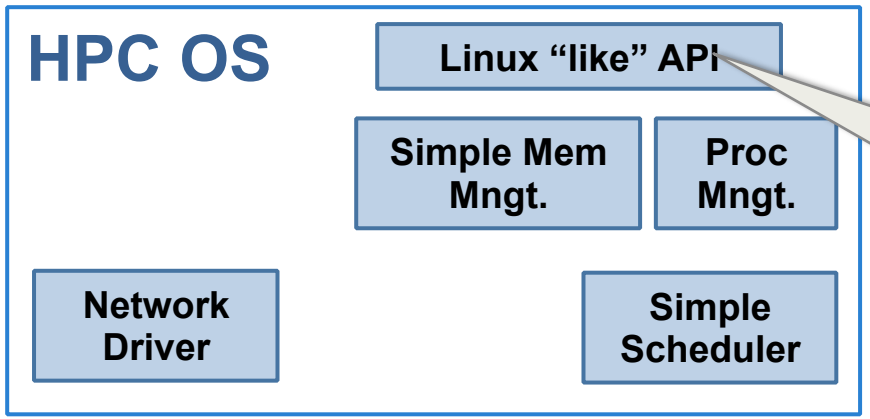
Background – HPC Node OS Architecture

- Traditionally: driven by the need for scalable, consistent performance for bulk-synchronous HPC



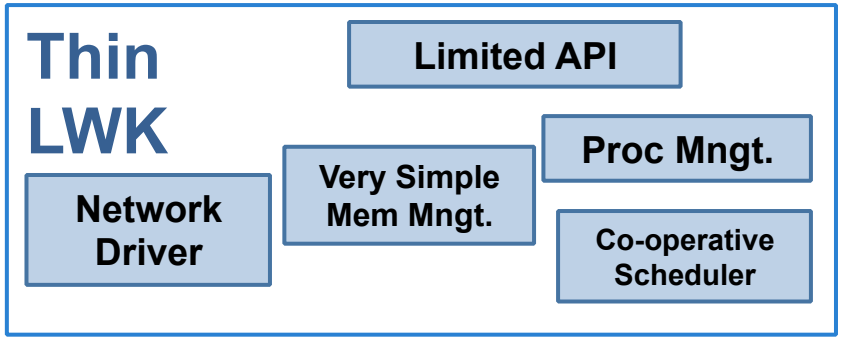
- Start from Linux and remove features impeding HPC performance
- Eliminate OS noise (daemons, timer IRQ, etc..), simplify memory mngt., simplify scheduler

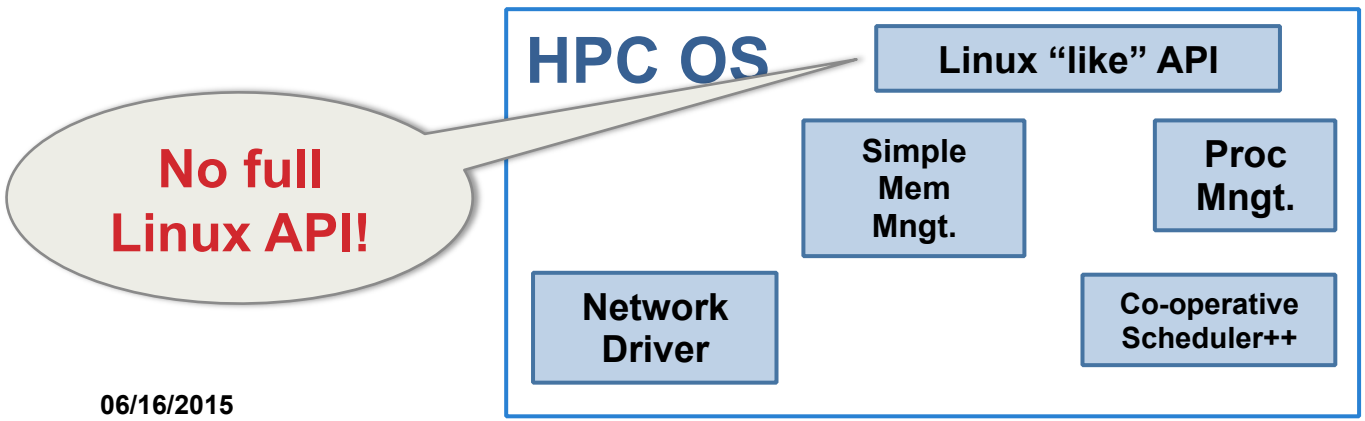
"Stripped down Linux" approach
(Cray's Extr. Scale Linux, Fujitsu's Linux, ZeptoOS, etc..)



Background – HPC Node OS Architecture

- **Traditionally: driven by the need for scalable, consistent performance for bulk-synchronous HPC**
  - **Start from a thin Light Weight Kernel (LWK) written from scratch and add features to provide a more Linux like I/F, but keep scalability**
  - **Support dynamic libraries, allow thread over-subscription, support for /proc filesys, etc..**





"Enhanced LWK" approach
(Catamount, CNK, etc..)

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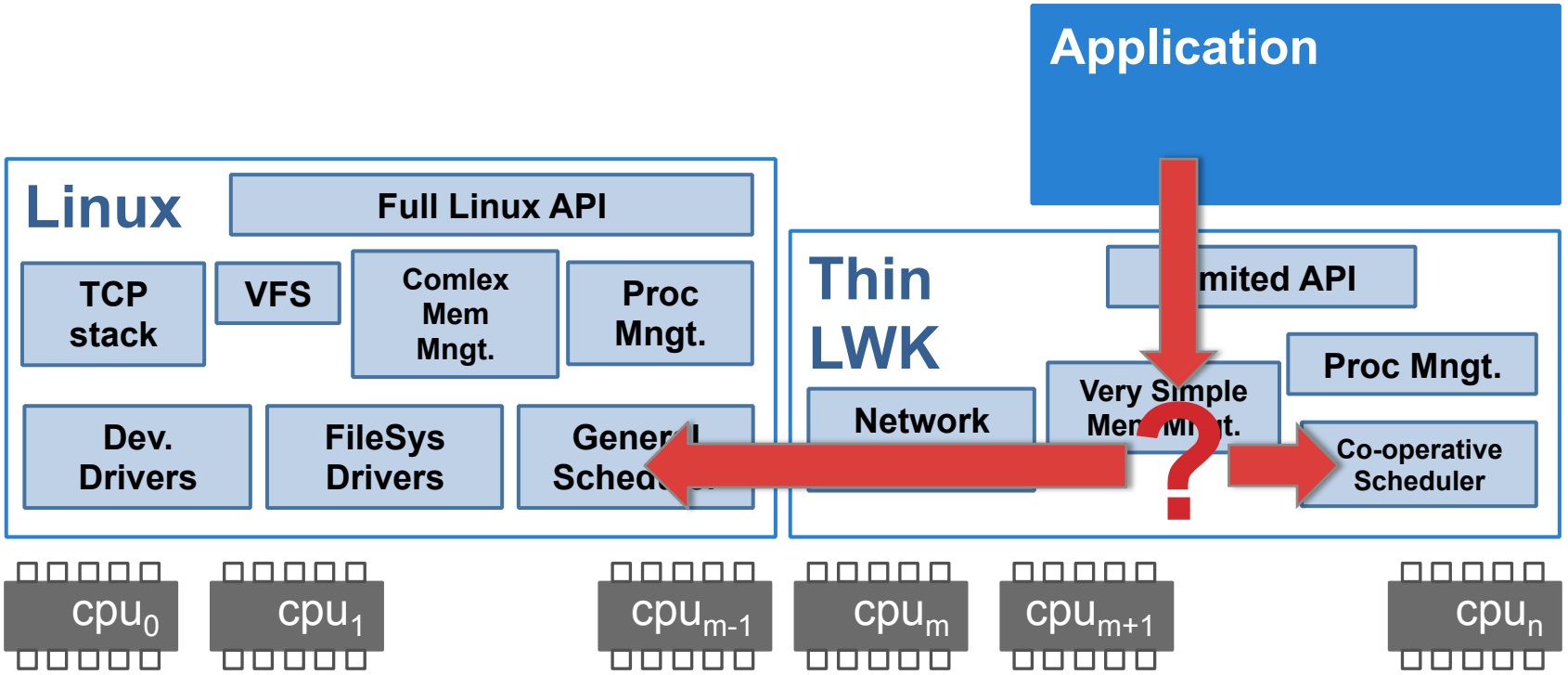
Hybrid Linux + LWK Approach

- With the abundance of CPU cores a new hybrid approach: run Linux and LWK side-by-side!
- Partition resources (CPU core, memory) explicitly
- Run HPC apps on LWK
- Selectively serve OS features with the help of Linux by offloading requests



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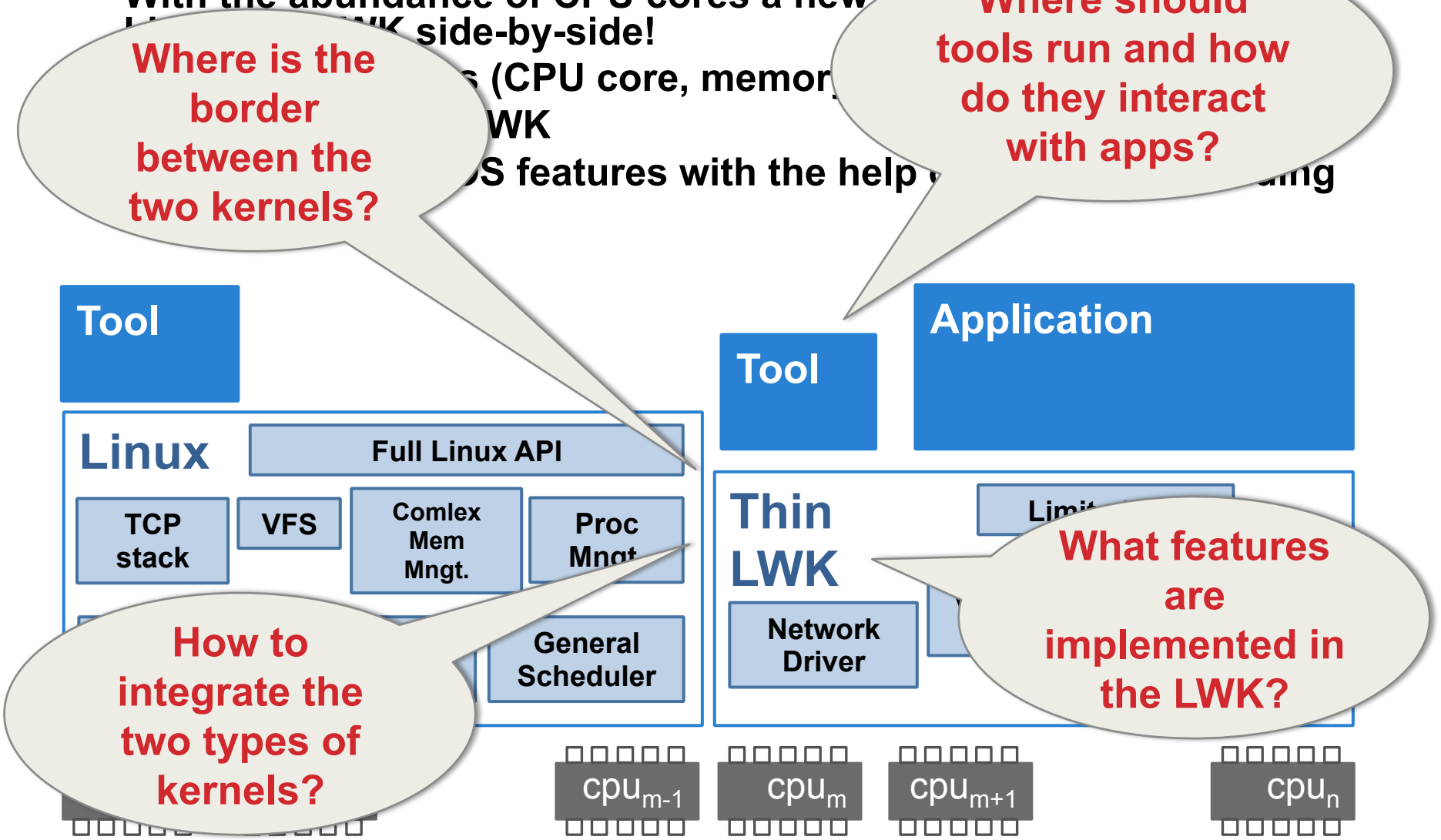
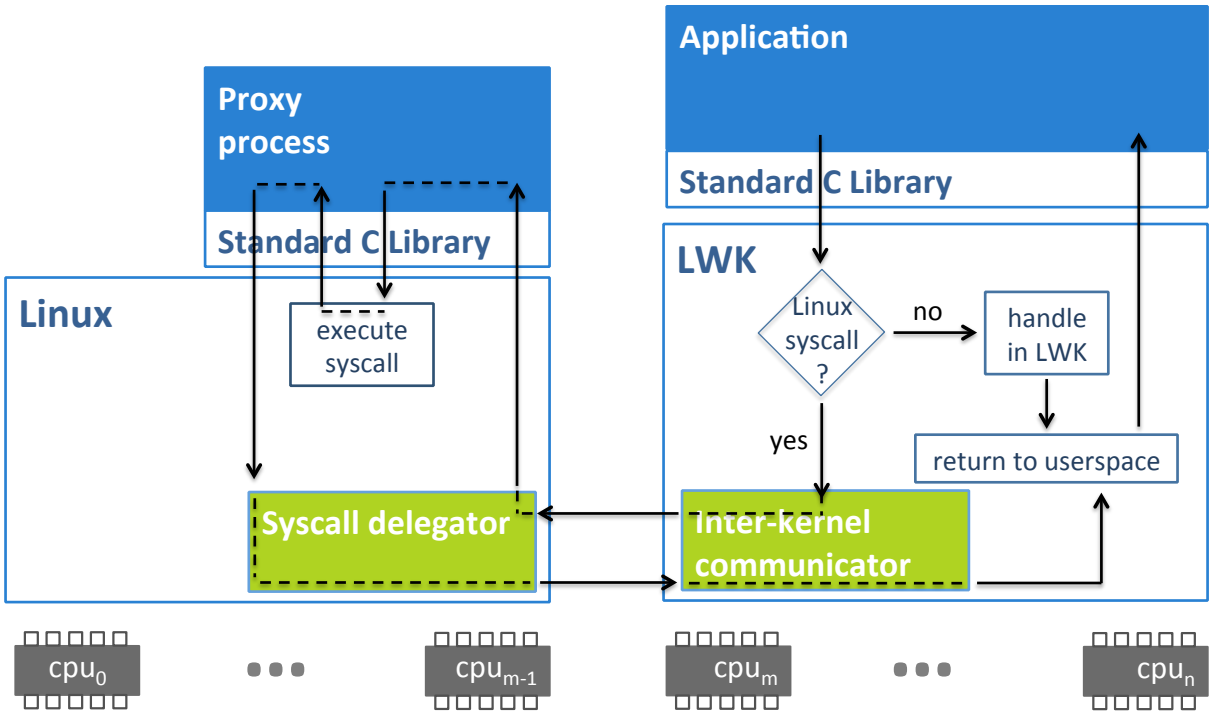


Linux + LWK: Requirements

- **Scalability and performance:**
  - System has to deliver LWK scalability, reliability and consistent performance
- **Linux compatibility:**
  - Support for POSIX and Linux APIs is an absolute must
- **Adaptability (a.k.a., nimbleness):**
  - System should seamlessly adapt to new HW features and SW needs
- **Maintainability:**
  - System should be highly maintainable, esp. tracking Linux changes

Linux + LWK: the Proxy Model

- LWK is completely independent from Linux
- Proxy process: serves as execution context for offloaded system calls
- Ensures that Linux kernel maintains necessary state information about the application (*i.e.*, file desc. table)

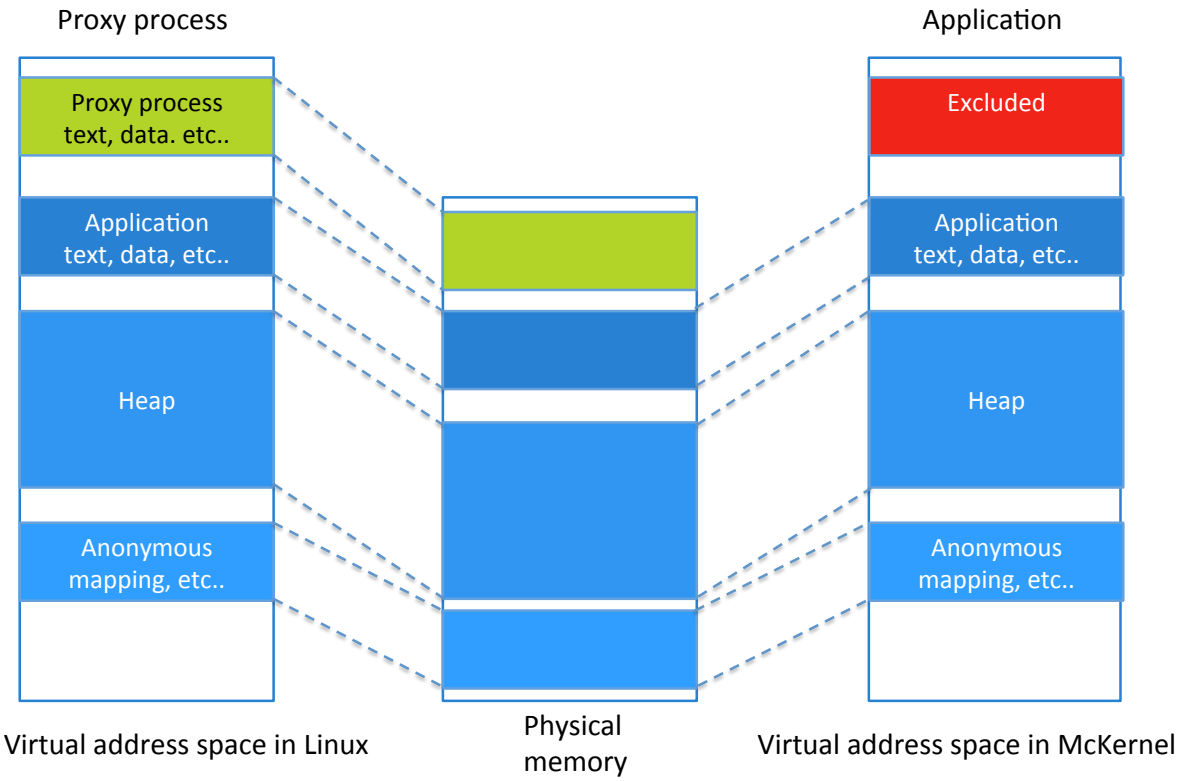


IHK/McKernel: an implementation of the Proxy Model

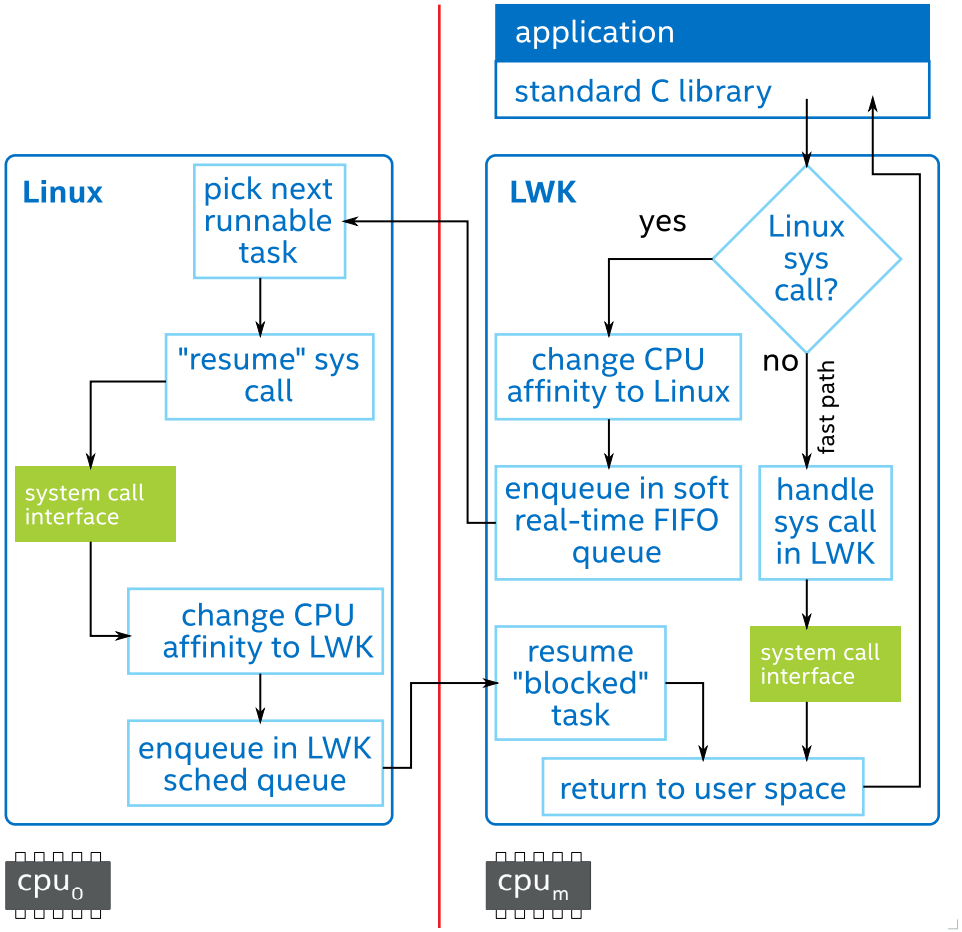
- **Interface for Heterogeneous Kernels (IHK):**
  - Low level software infrastructure
  - Allows partitioning SMP chips (using the Linux hotplug service)
  - Enables management of resources and light-weight kernels
    - Create OS instances, assign resources
    - Load kernel images, boot OS, etc..
  - Provides low-level Inter-Kernel Communication (IKC) layer
- **McKernel:**
  - A lightweight kernel designed for HPC
  - Booted from IHK and requires Linux' presence
  - Only performance sensitive syscalls (MM, PM, perf counters) impl.
    - Rest offloaded to Linux
  - Simple co-operative round-robin scheduler

IHK/McKernel: unified address space

- **System call offloading: what to do with pointers?**
  - Linux kernel may access them (*i.e.*, copy_from_user(), etc..)
- **User-space virtual to physical mappings are set up to be the same in Linux so that the proxy process can access syscall arguments**
- **A pseudo file mapping in mcexec (proxy process) covers the entire user-space of McKernel. When page fault occurs we trap the handler and set up mappings so that they point to the same physical pages**



Linux + LWK: mOS' Direct Model



- **Tight integration between LWK and Linux**
- **LWK passes kernel data structures to Linux when offloading system calls (Evanescence)**
  - *i.e.*, migrates the task_struct
- **LWK is "compiled-in"**
- **Anticipated: various kernel features will be available directly (*e.g.*, no need to deal with pointers in syscall offloading, etc..)**
- **CPU cores and memory are isolated but Linux is aware of them, Linux IRQs are not directed to LWK cores**
- **Which OS services are implemented in LWK and to what extent the LWK implementation is restricted are somewhat unclear**

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Comparison: Linux compatibility

- **POSIX and Linux API compatibility on LWK:**
  - Correct syscall API and execution (involving offload)
  - Valid signaling behavior
  - Availability of **/proc** and **/sys** statistical information
  - Availability of the **ptrace** interface (many tools rely on this)
  - Virtual dynamics objects (VDSO) page
  - Performance counters (PAPI, etc..)

- **Proxy model (McKernel):**
  - Significant implementation effort because kernel code is isolated
  - /proc and /sys:
    - Redirections from the syscall offload kernel module
      - Data needs to be obtained from McKernel
  - How far should McKernel present itself as “stand alone”? /proc/cpuid, etc..
- **mOS:**
  - Lot of things are expected to “fall out” for free
  - /proc and /sys can be directly accessed due to shared kernel structures, VDSO just works
  - Will signaling/ptrace work?
    - Cross-kernel IPIs?

Comparison: Flexibility

- **LWK Flexibility (a.k.a., nimbleness)**
  - Ability to easily adapt to new requirements
  - Rapid prototyping for unconventional hardware
    - Heterogeneous cores, deep memory hierarchies, multiple cache coherence domains, etc..
  - Easy experimentation for exotic runtimes
  - Small LWK codebase is favored

- **McKernel:**
  - Standalone kernel code with small codebase
    - IHK+McKernel: ~50k lines
  - Full control over implementation
  - Allows proprietary kernel images as well
- **mOS:**
  - Tighter integration with Linux (data structures) could limit flexibility
    - Translation between mOS and Linux kernel structures before and after syscall offloading could alleviate the issue

Comparison: Linux modifications

- **Required Linux modifications**
  - It's hard to keep track upstream Linux changes
  - Keeping the number of changes minimal is first priority

- **IHK/McKernel:**
  - No changes to Linux kernel but unexported symbols are accessed
    - irq_desc_tree, wakeup_secondary_cpu_via_init(), etc..

- **mOS:**
  - Evanescence requires some changes (~150 lines) to Linux kernel
    - System call wrapper macros for offloading
  - mOS' objective is to implement most LWK functions isolated from the Linux codebase

Comparison: LWK reboot

- **LWK reboot capability**
  - Reboot can provide a clean, well defined state
  - Allows easy deployment of different/customized LWK kernel images
  - Rebooting the LWK between jobs can lead to more predictable application behavior
  - “Reboot every time” design may simplify the LWK, no need for concepts such as switching between apps/users

- **Proxy model (McKernel):**
  - Warm rebooting LWK cores is supported
  - Can solve problems where otherwise rebooting the node would be required (inconsistency in LWK, etc..)
- **mOS:**
  - LWK cores do not go through their own trampoline code → no rebooting in its strict sense
  - CPU hotplug/re-plug may be used

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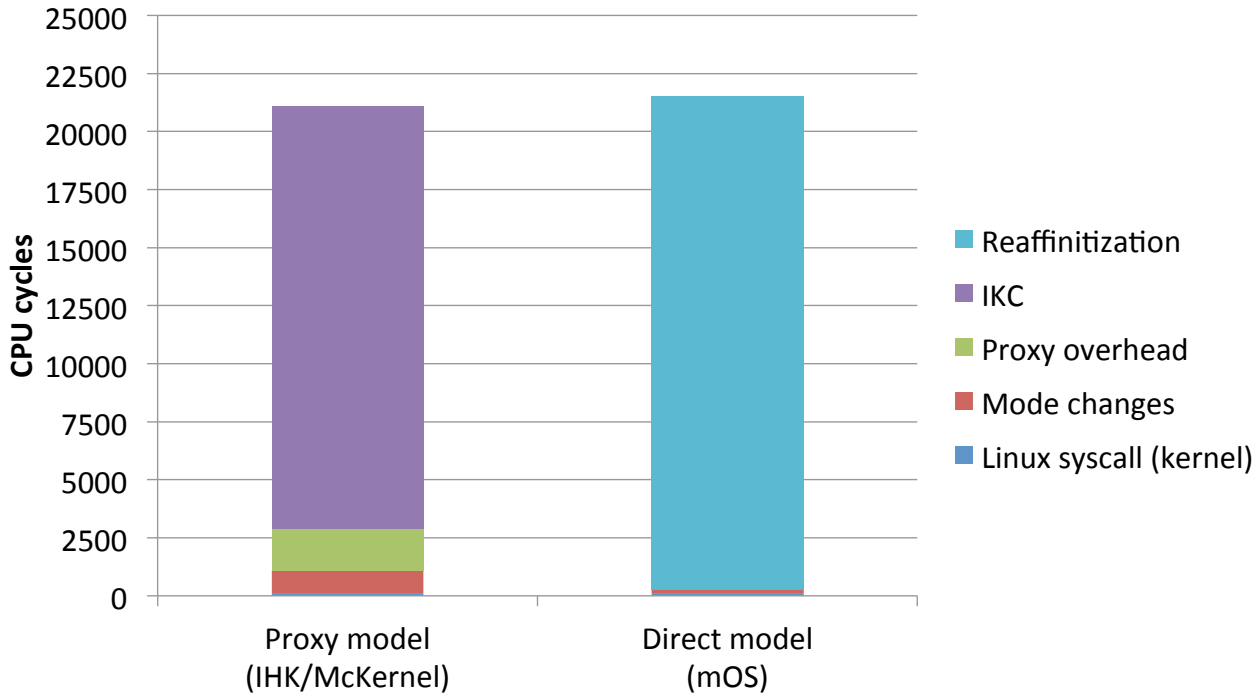
Evaluation

- HW: Ivy Bridge (E5-2670) – same LWK CPU cores in each measurements
- Test: simple “empty” syscall offloading cost comparison



- Surprisingly similar performance!
- mOS offload performance will probably improve in the future
- IHK/McKernel plans for evaluating MONITOR/MWAIT

Conclusion

- **Need for enhanced system software to meet HW and SW requirements of exascale and beyond**
- **Hybrid Linux+LWK approach proposed to provide LWK performance but to retain Linux APIs at the same time**
- **Explored design alternatives and their trade-offs**

- **Direct model (mOS @ Intel)**
  - Less development effort for Linux compatibility and tools support
- **Proxy model (IHK/McKernel @ RIKEN)**
  - Retains full control over the code base of the LWK and thus has a higher degree of flexibility

Thank you for your attention!
Questions?