Quest-V: A Secure and Predictable System for IoT and Beyond

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Goals

- Develop system for high-confidence (embedded) systems
  - Mixed criticalities (timeliness and safety)

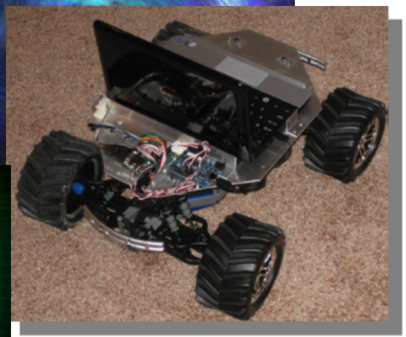
- Predictable – real-time support
- Secure – resistant to component failures & malicious attacks
- Self-healing
- Online recovery of software component failures

Target Applications

- Healthcare
- Avionics
- Automotive
- Factory automation
- Robotics
- Space exploration
- Secure/safety-critical domains
- Internet-of-Things (IoT)








Internet of Things

- Number of Internet-connected devices

> 12.5 billion in 2010

- World population > 7 billion (2015)
- Cisco predicts 50 billion Internet devices by

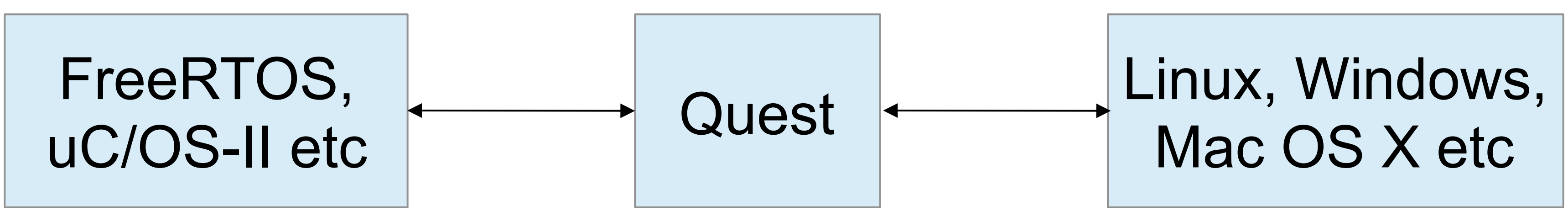
2020

Challenges:

- **Secure** management of vast quantities of data
- **Reliable** + **predictable** data exchange b/w "smart" devices

In the Beginning...Quest

- Initially a “small” RTOS
- ~30KB ROM image for uniprocessor version
- Page-based address spaces
- Threads
- Dual-mode kernel-user separation
- Real-time Virtual CPU (VCPU) Scheduling
- Later SMP support
- LAPIC timing



From Quest to Quest-V

- Quest-V for multi-/many-core processors
  - Distributed system on a chip
  - Time as a first-class resource
    - Cycle-accurate time accountability
  - Separate **sandbox** kernels for system components
  - Memory isolation using h/w-assisted memory virtualization
  - Also CPU, I/O, cache partitioning
- Focus on **safety**, **efficiency**, **predictability** + **security**

Related Work

- Existing virtualized solutions for resource partitioning
  - Wind River Hypervisor, XtratuM, PikeOS, Mentor Graphics Hypervisor
  - Xen, Oracle PDOMs, IBM LPARs
  - Muen, (Siemens) Jailhouse

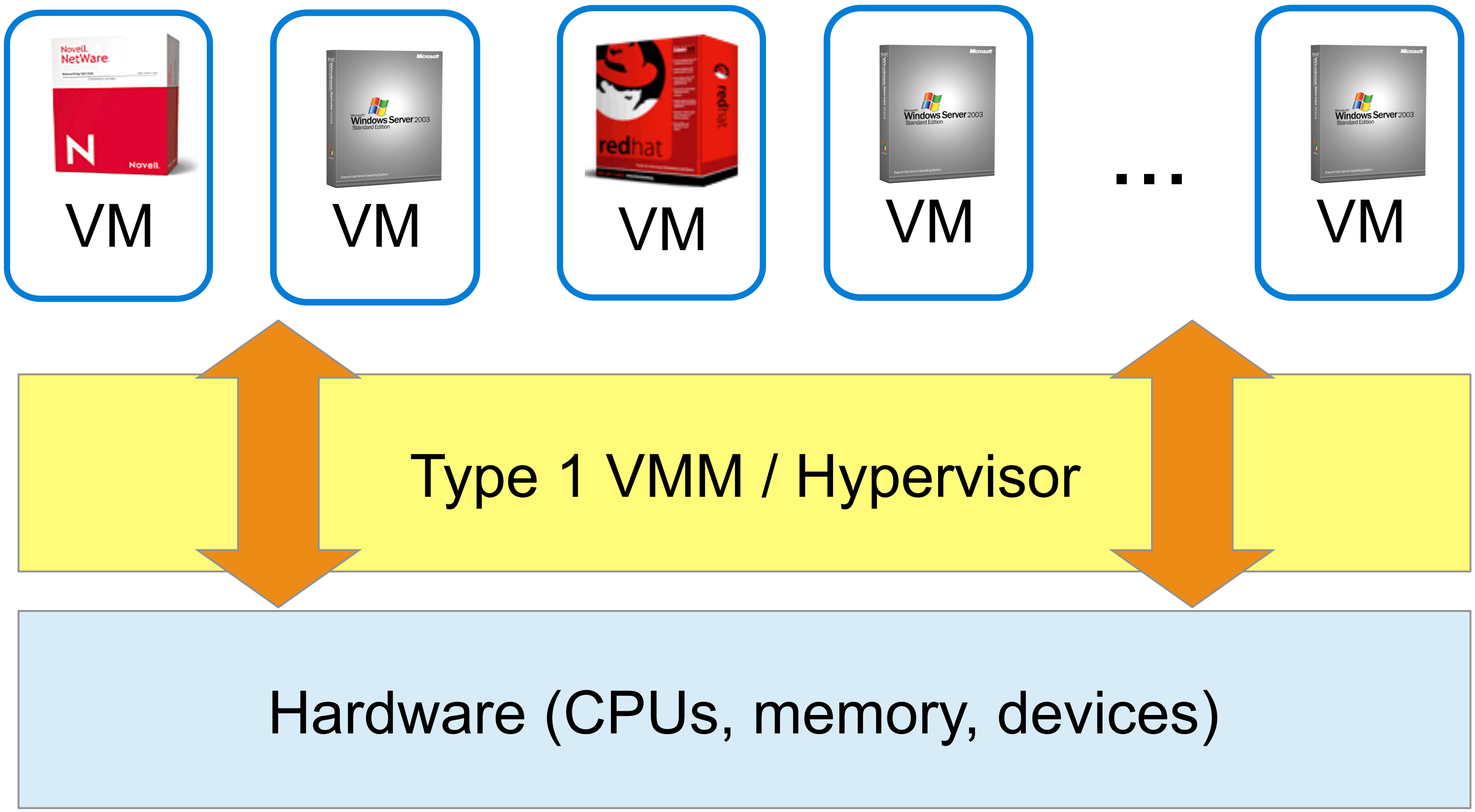
Problem

Traditional Virtual Machine approaches **too expensive**

- Require traps to VMM (a.k.a. hypervisor) to mux & manage machine resources for multiple guests
- e.g., ~1500 clock cycles VM-Enter/Exit on Xeon E5506

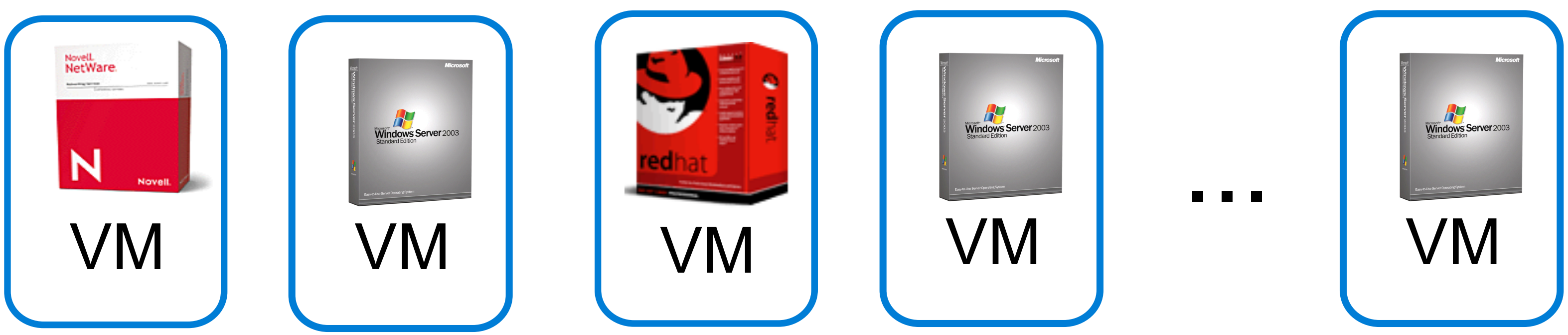
Traditional Virtual Machine approaches **too memory intensive** for embedded systems in areas such as IoT!

Traditional Approach (Type 1 VMM)



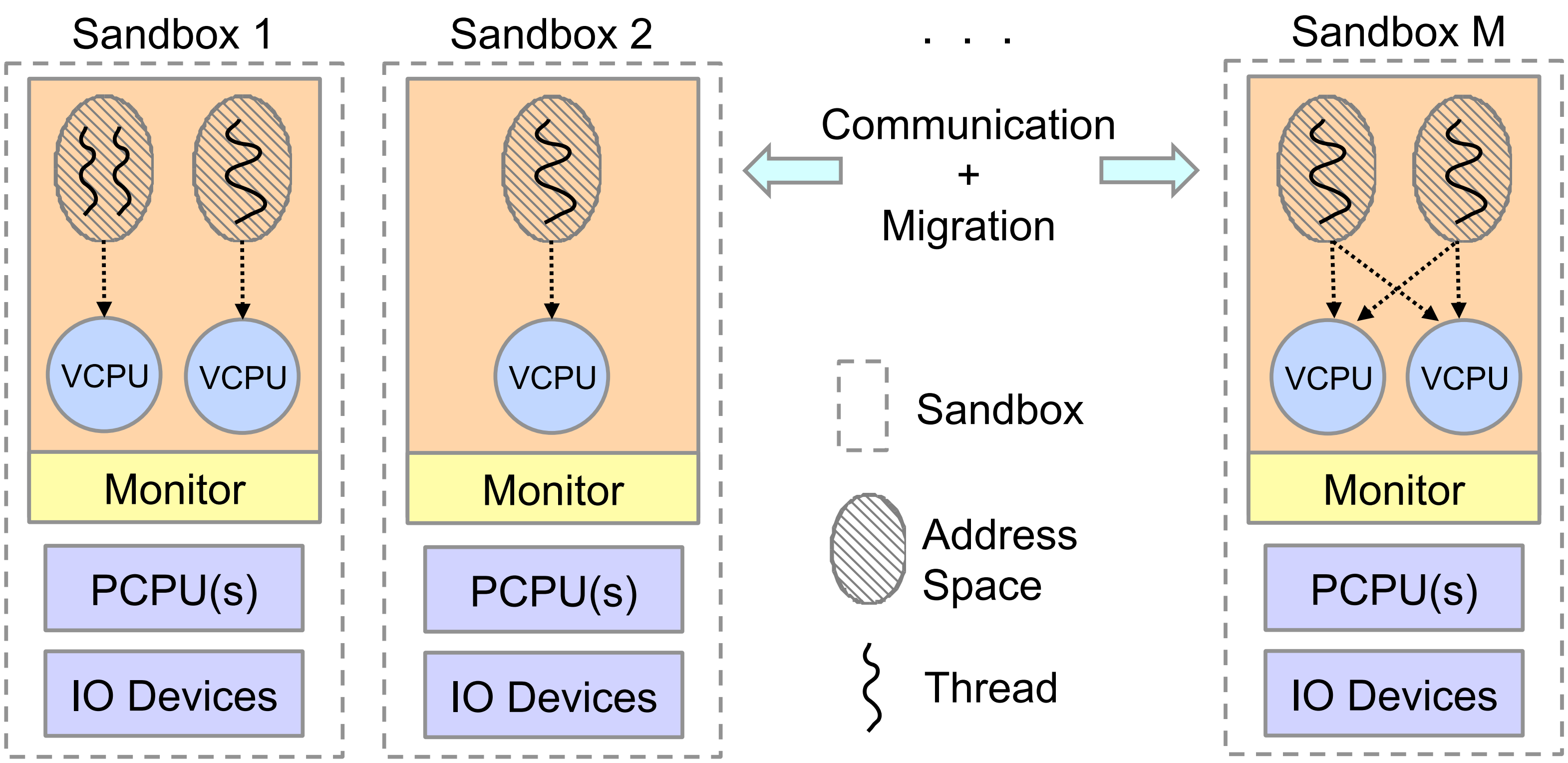
Quest-V Approach

Eliminates hypervisor intervention during normal virtual machine operations



Hardware (CPUs, memory, devices)

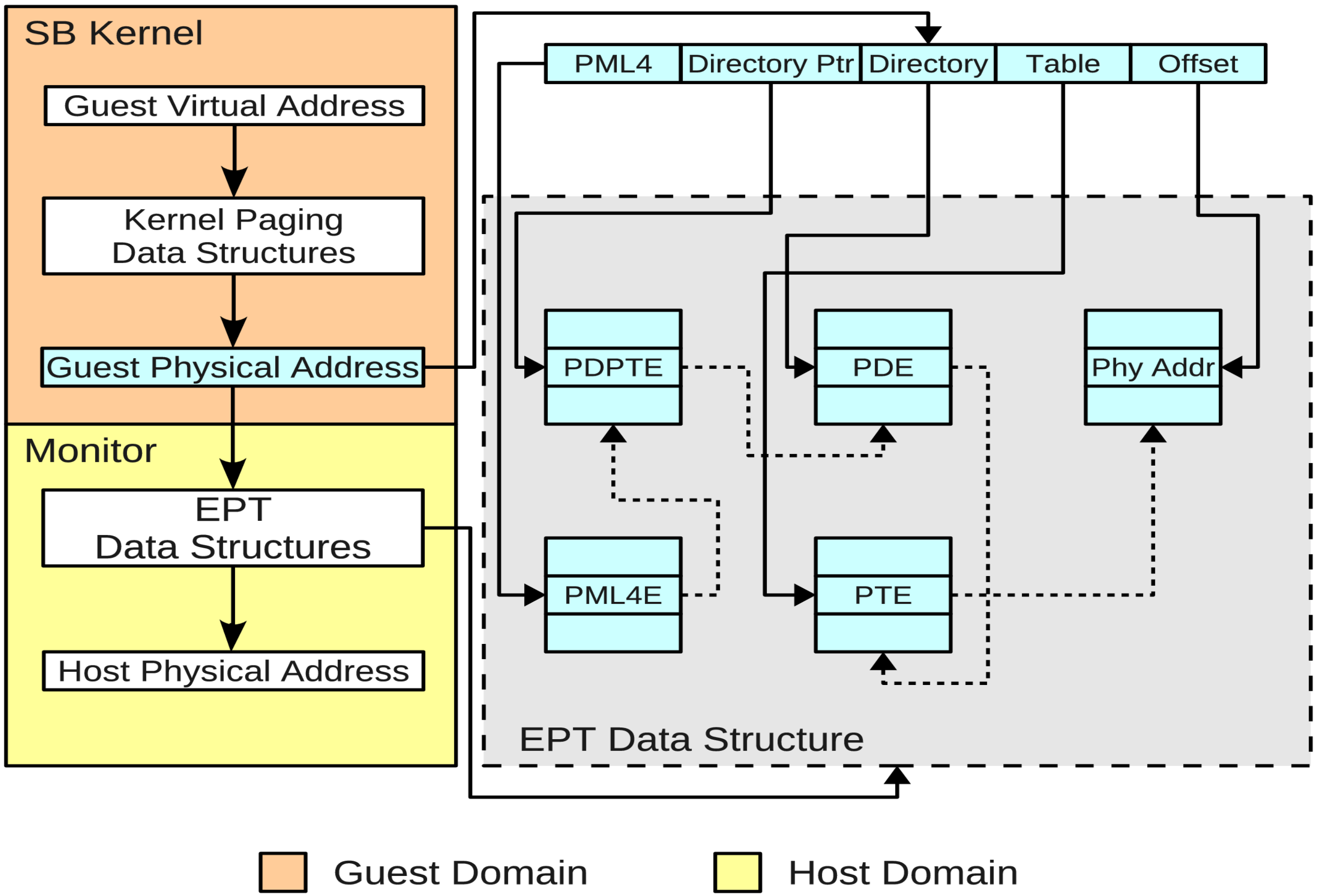
Quest-V Architecture Overview



Memory Partitioning

- Guest kernel page tables for GVA-to-GPA translation
- EPTs (a.k.a. shadow page tables) for GPA-to-HPA translation
  - EPTs modifiable only by monitors
  - Intel VT-x: 1GB address spaces require 12KB EPTs w/ 2MB superpaging

Quest-V Memory Partitioning



I/O Partitioning

- Device interrupts directed to each sandbox
  - Use I/O APIC redirection tables
  - Eliminates monitor from control path
- EPTs prevent unauthorized updates to I/O APIC memory area by guest kernels

- Port-addressed devices use in/out instructions
- VMCS configured to cause monitor trap for specific port addresses
- Monitor maintains device "blacklist" for each sandbox
  - DeviceID + VendorID of restricted PCI devices

CPU Partitioning

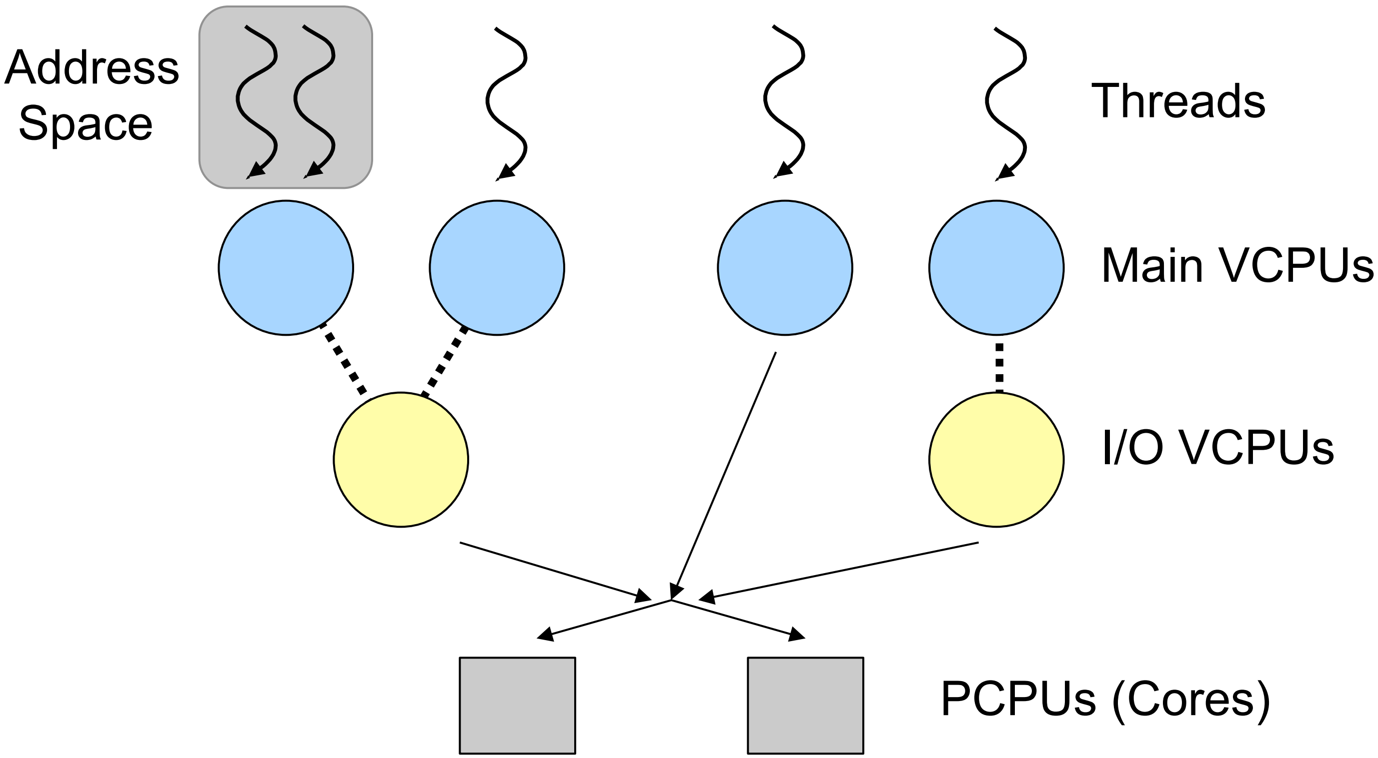
- Scheduling local to each sandbox
  - partitioned rather than global
  - avoids monitor intervention

- Uses real-time VCPU approach for Quest native kernels **[RTAS'11]**

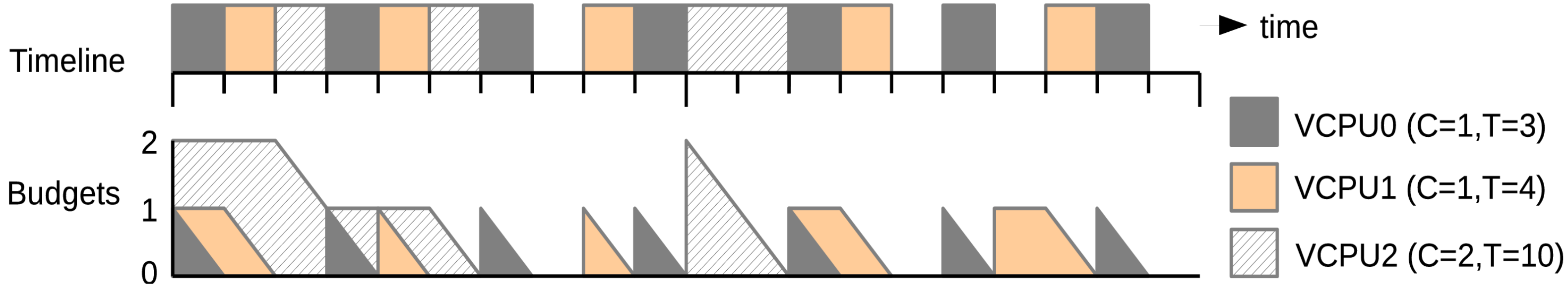
Predictability

- VCPUs for budgeted real-time execution of threads and system events (e.g., interrupts)
  - Threads mapped to VCPUs
  - VCPUs mapped to physical cores
- Sandbox kernels perform local scheduling on assigned cores
  - Avoid VM-Exits to Monitor – eliminate cache/ TLB flushes

VCPUs in Quest(-V)



Example VCPU Schedule



Utilization Bound Test

- Sandbox with 1 PCPU, n Main VCPUs, and m I/O VCPUs
  - Ci = Budget Capacity of Vi
  - Ti = Replenishment Period of Vi
  - Main VCPU, Vi
  - Uj = Utilization factor for I/O VCPU, Vj

$$\sum_{i=0}^{n-1} \frac{Ci}{Ti} + \sum_{j=0}^{m-1} (2 - Uj) \cdot Uj \leq n \cdot \left(\sqrt[n]{2} - 1 \right)$$

Cache Partitioning

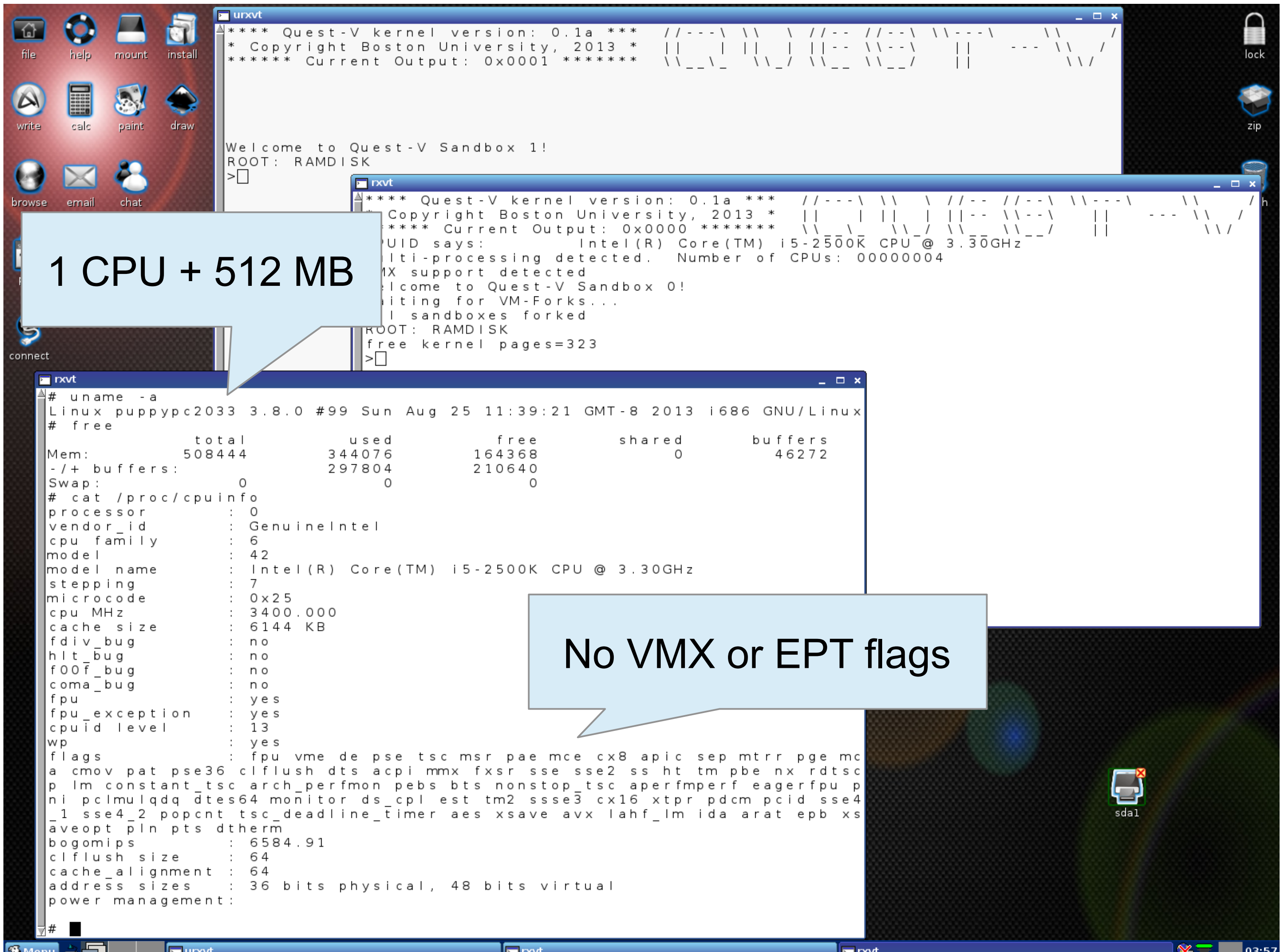
- Shared caches controlled using color-aware memory allocator **[COLORIS – PACT'14]**
- Cache occupancy prediction based on h/w performance counters
  - $E' = E + (1\text{-}E/C) * m_l - E/C * m_o$
  - Enhanced with hits + misses

  [Book Chapter, OSR'11, PACT'10]

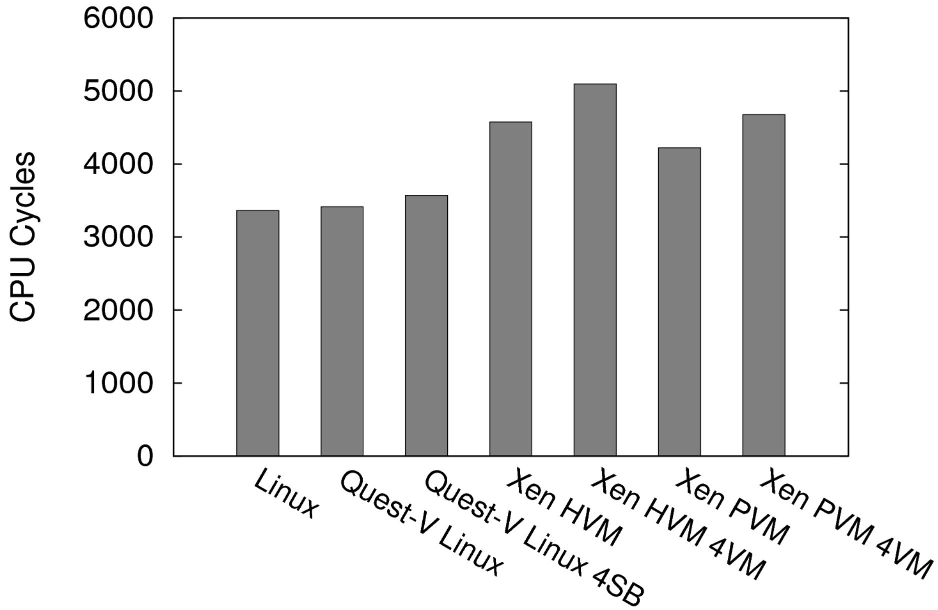
Linux Front End

- For low criticality legacy services
- Based on Puppy Linux 3.8.0
- Runs entirely out of RAM including root filesystem
- Low-cost paravirtualization
  - less than 100 lines
  - Restrict observable memory
  - Adjust DMA offsets
- Grant access to VGA framebuffer + GPU
- Quest native SBs tunnel terminal I/O to Linux via shared memory using special drivers

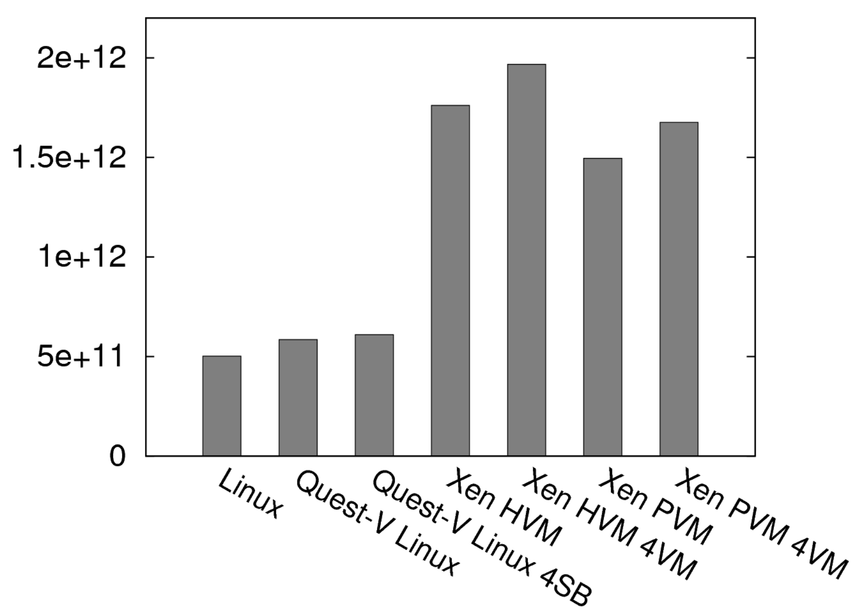
Quest-V Linux Screenshot



Quest-V Performance



100 Million Page Faults



1 Million *fork-exec-exit* Calls

Quest-V Summary

- Separation kernel built from scratch
  - Distributed system on a chip
  - Uses (optional) h/w virtualization to partition resources into sandboxes
  - Protected comms channels b/w sandboxes

- Sandboxes can have different criticalities
  - Linux front-end for less critical legacy services
- Sandboxes responsible for local resource management
  - avoids monitor involvement

Proposed Work

- Port of Quest to Intel Galileo [Done]
- Qduino API [Ongoing]
- Port of Quest(-V) to Intel Edison and Minnowboard Max [Started]
- IoT Applications: 3D printing / manufacturing, robotics, secure home automation, etc [To Do]
- (Secure) Information Flow Analysis [To Do]
- Real-time Communication [Ongoing]

Quest on Galileo

- Porting Quest to the Galileo board:
  - Added multiboot support back to 32-bit GRUB EFI (GRUB Legacy)
  - Developed I2C, SPI controller drivers
  - Developed Cypress GPIO Expander and AD7298 ADC drivers

- Original Arduino API Support
- New real-time multithreaded Qduino API

Qduino

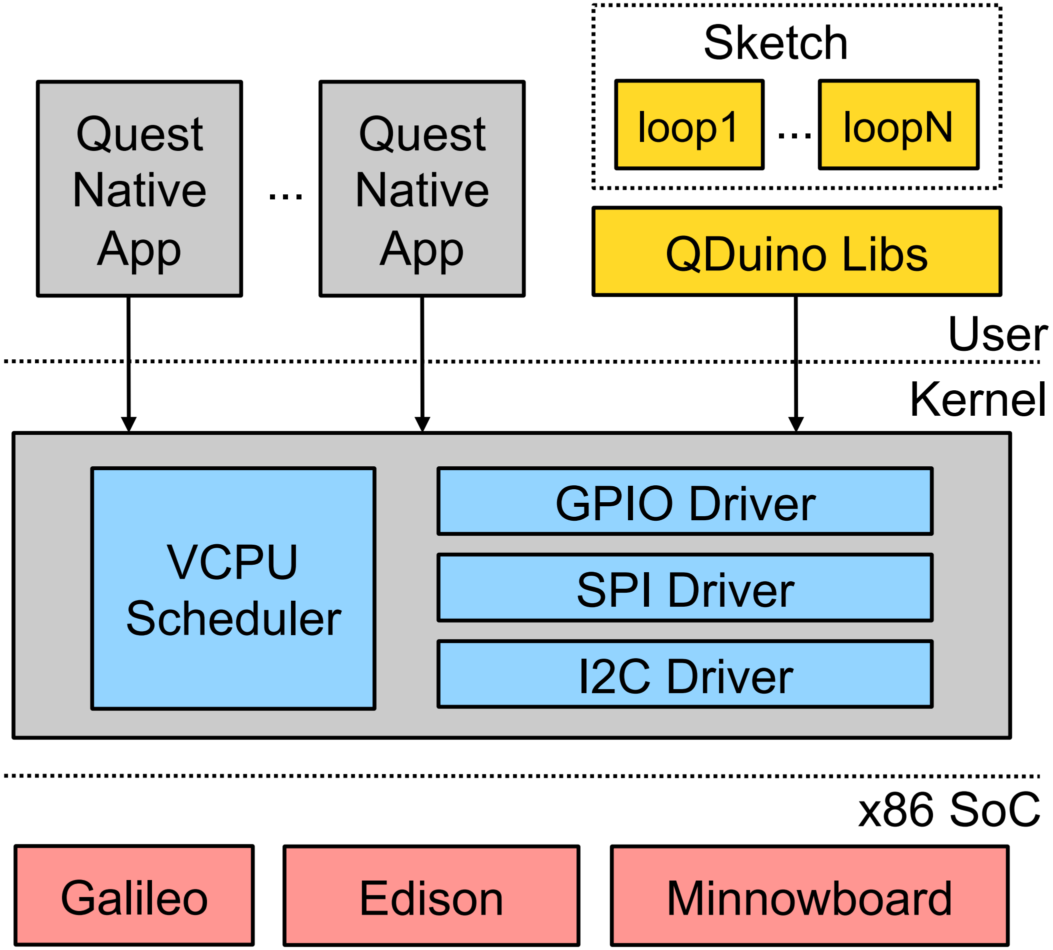
- Qduino – Enhanced Arduino API for Quest
  - Parallel and predictable loop execution
  - Real-time communication b/w loops
  - Predictable and efficient interrupt management
  - Real-time event delivery
  - Simplifies multithreaded real-time programming

Qduino Multi-loop Example

- Multiple loop sketch example:

```
loop (1, 40, 100) {  /* VCPU: C = 40, T = 100 */
  digitalWrite (LED1, HIGH);
  ...  /* Blink LED1 */
}
loop (2, 20, 100) {  /* VCPU: C = 20, T = 100 */
  analogWrite (LED2, brightness);
  ...  /* Change brightness of LED2 */
}
setup () {
  pinMode (LED1, OUTPUT);
  pinMode (LED2, OUTPUT);
}
```

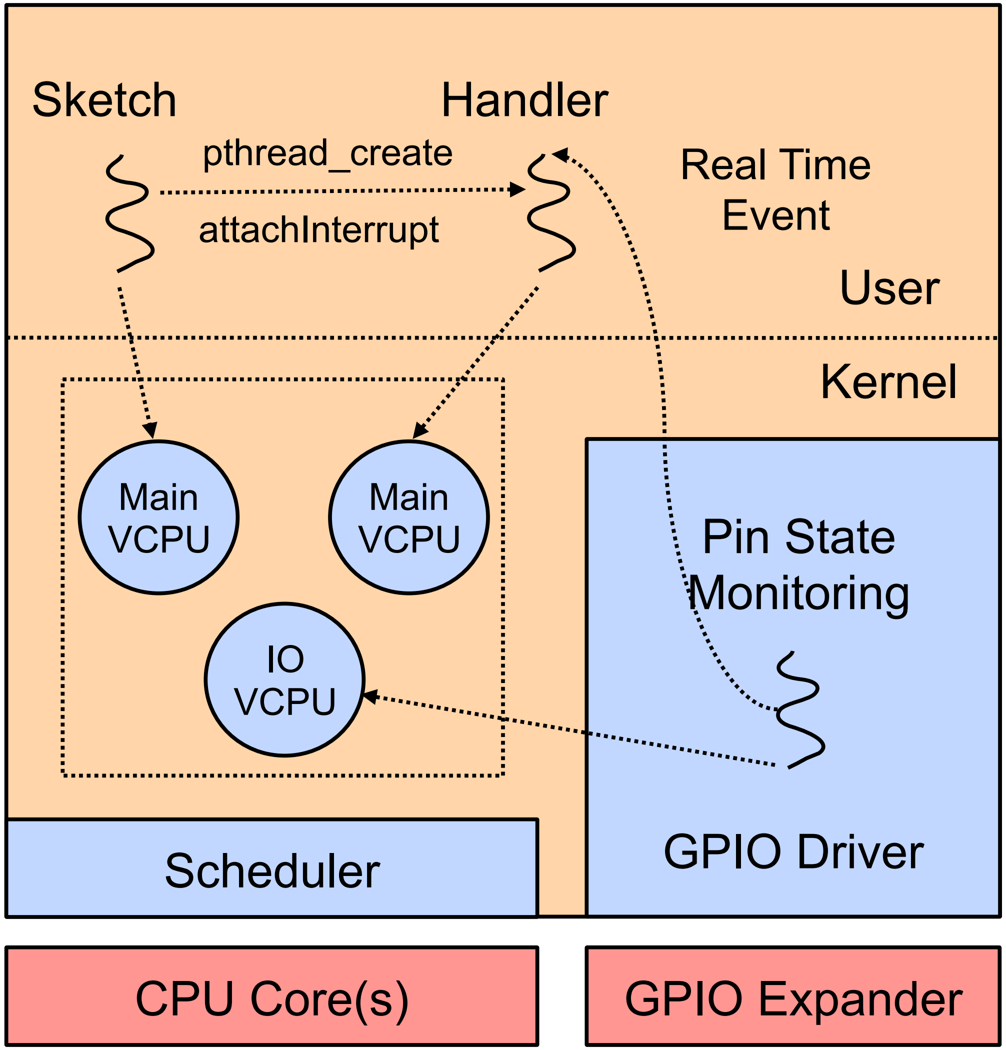
Qduino Organization



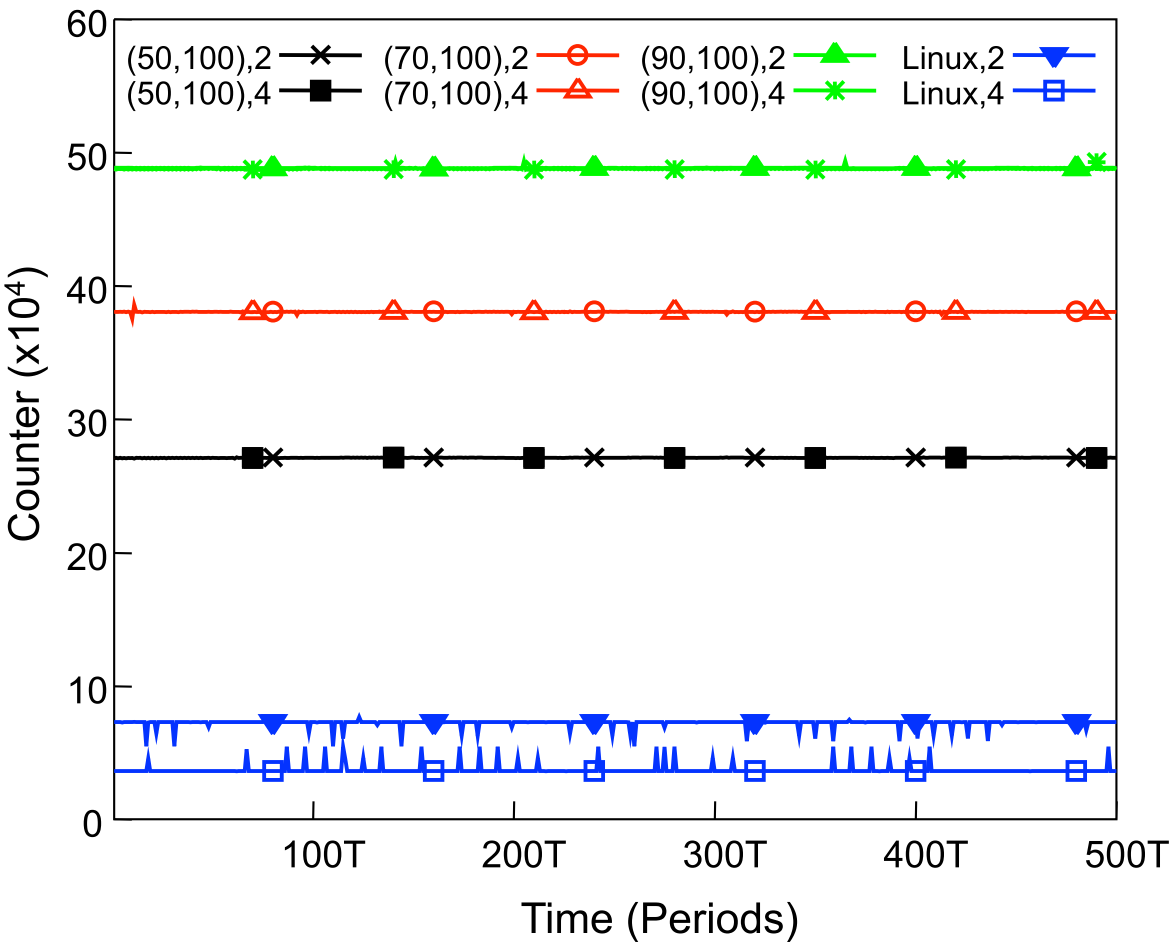
Qduino New APIs

Function Signatures	Category
• loop(loop_id, C, T)	Structure
• interruptsVcpu(C,T) • attachInterruptVcpu(pin,ISR,mode,C,T)	Interrupt
• spinlockInit(lock) • spinlockLock(lock) • spinlockUnlock(lock)	Spinlock
• channelWrite(channel,item) • item channelRead(channel)	Four-slot
• ringbufInit(buffer,size) • ringbufWrite(buffer,item) • ringbufRead(buffer,item)	Ring buffer

Qduino Event Handling



Qduino Temporal Isolation

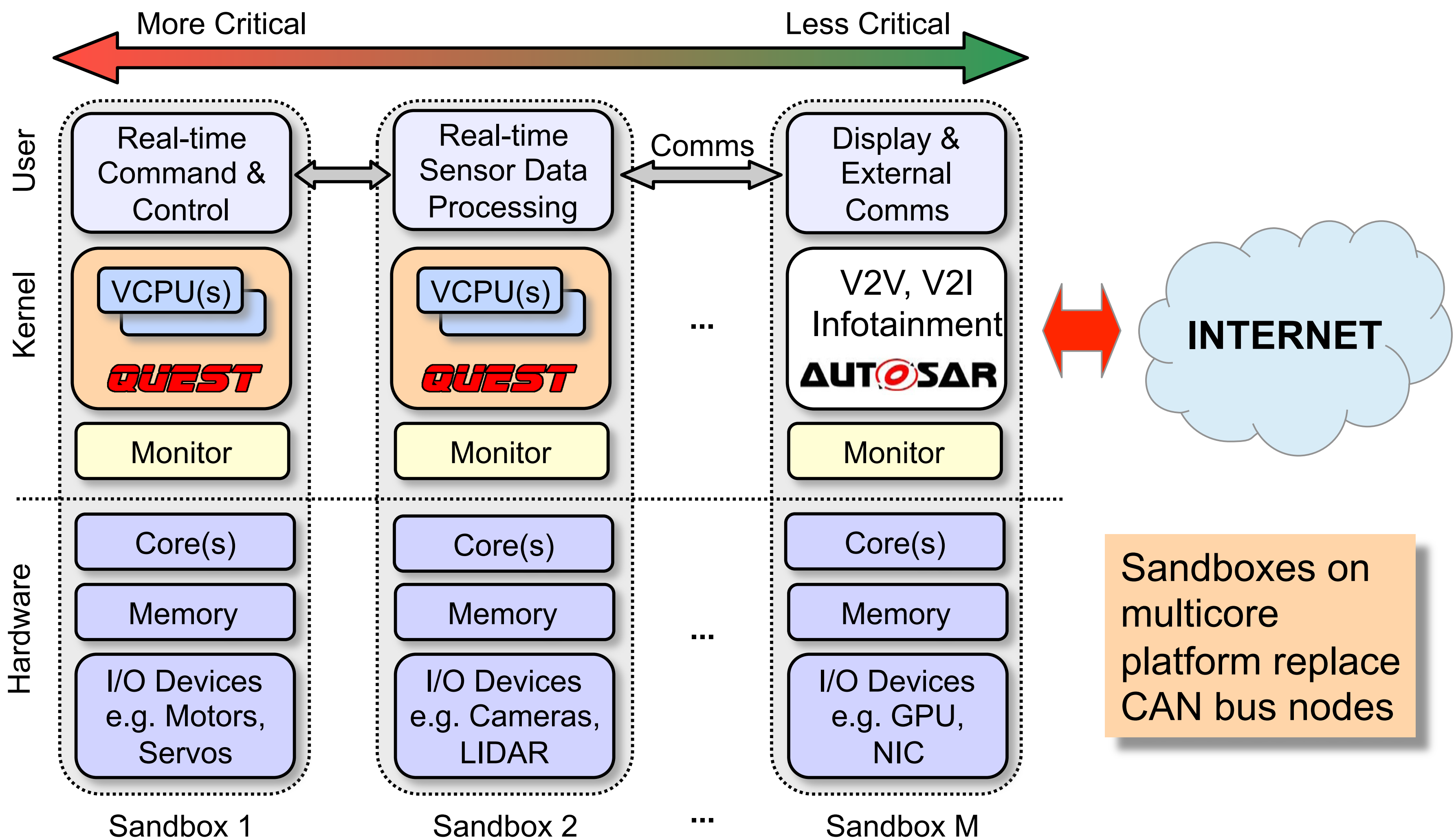


- Foreground loop increments counter during loop period
- 2-4 background loops act as potential interference, consuming remaining CPU capacity
- No temporal isolation or timing guarantees w/ Linux

Possible Use Cases

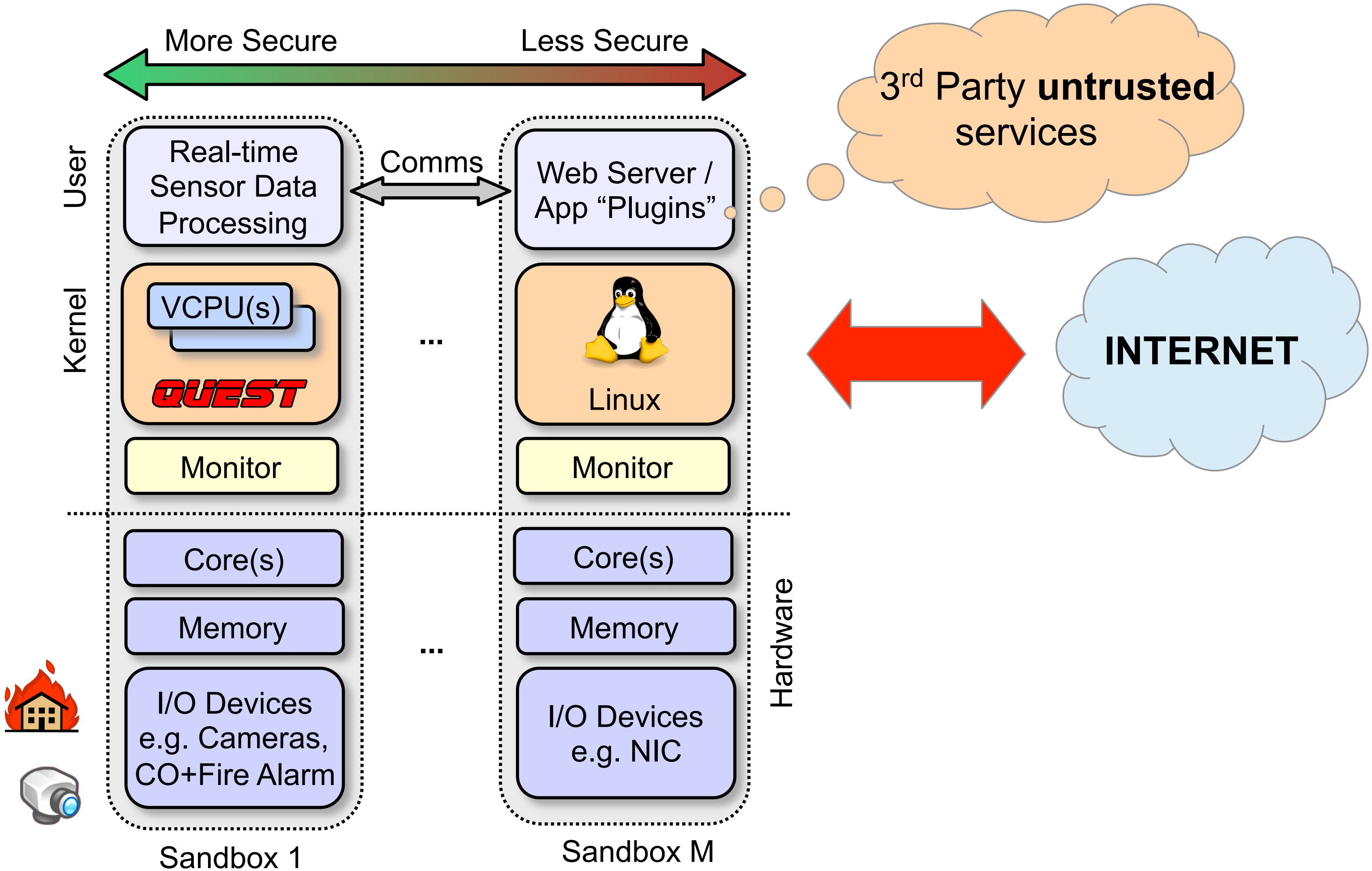
- Mixed-criticality automotive system
- Secure home automation
- 3D printer controller
- IoT interoperability sandboxing
    - Secure virtual networks of untrusted devices
- Many others...

Mixed-Criticality Automotive System



Sandboxes on multicore platform replace CAN bus nodes

Secure Home Automation



Secure Home Automation

- Home equipped w/ cameras, alarms, window/ door actuators, HVAC + appliance controls
- "Home owner" sandbox(es) for localized control of data, sensors + actuators
  - e.g., smartphone ←→ appliance control
- 3rd party sandbox(es) for plugin app services
  - e.g., Emergency (police/fire/ambulance) callouts

Secure Home Automation

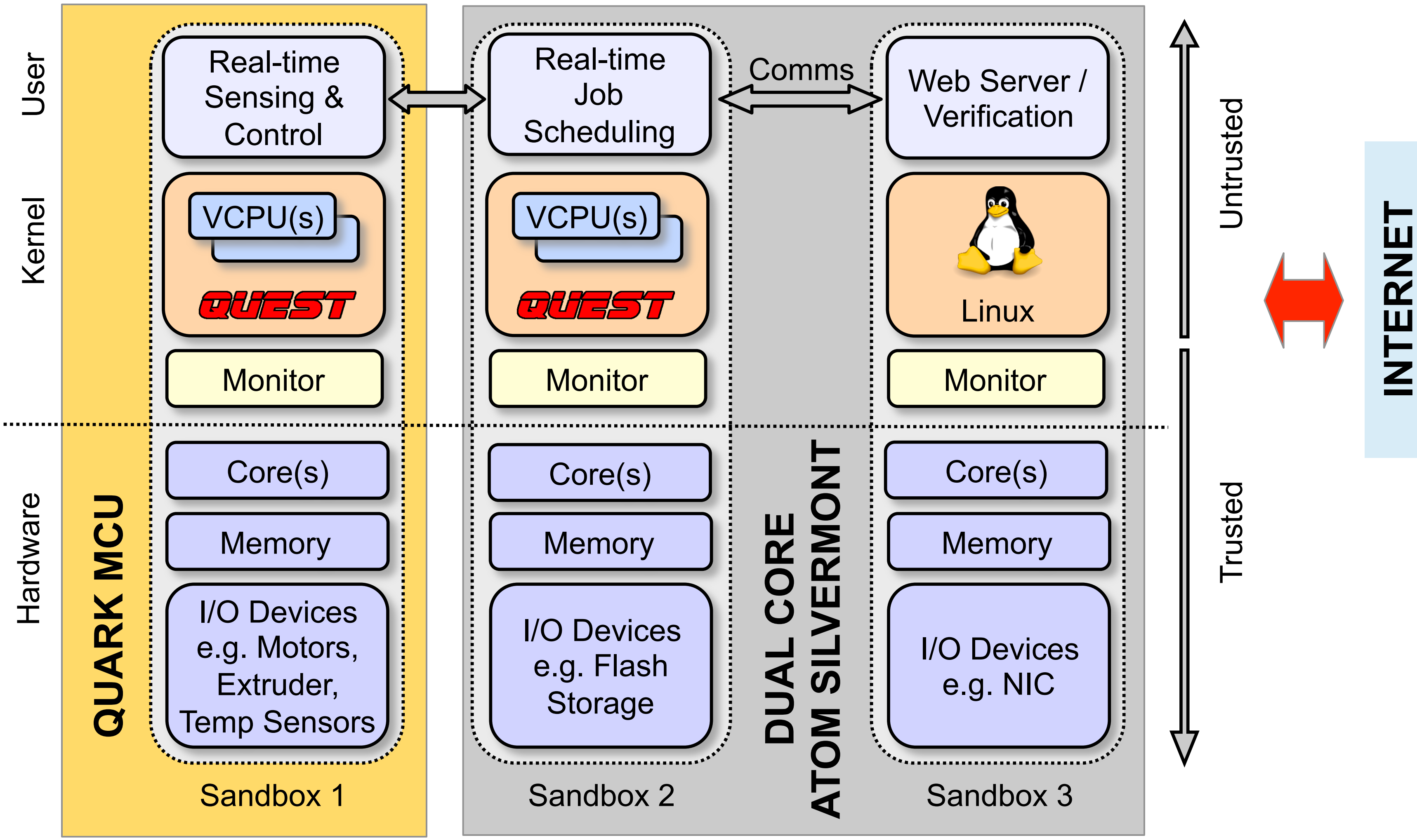
- Challenges:
  - Prevent homeowner generating false alarms
    - Apply penalties from service provider
  - Prevent 3rd parties accessing sensitive homeowner data (e.g., raw camera feeds)
    - Enforce secure inter-sandbox comms
    - Require services across sandboxes to be digitally signed by separate entities (non-collusion)

Secure Home Automation

- External system interface via public Internet only accesses 3rd party (untrusted) sandboxes
- Internal system interface via home network accesses trusted sandboxes

- Replicated monitors observe suspicious activity
  - e.g., high frequency access to “root” mode (monitor) via VM-exits
- Monitors akin to security guards
  - An attacker would have to compromise all such guards to prevent system recovery

Edison 3D Printer Controller



Distributed Virtual Manufacturing

- Extend 3D print service to distributed “customizable” one-off manufacturing
  - A “Kinkos” 3D printing/manufacturing service
- Submit requests via web interface
  - Need to verify correctness
- Verified requests spooled for processing
- Use real-time comms + Qduino for real-time machine control
  - Possible to form “job shop” style assembly lines

IoT Interoperability Sandboxing

- Collaborative open-source frameworks
  - IoTivity (Open Interconnect Consortium: Intel, Samsung, Cisco, GE + many others)
  - Alljoyn (Allseen Alliance), 160+ partners
  - Communication across different transport media, OSes, and protocols
  - Microsoft Device System Bridges (DSBs) for Z-wave and BACnet
- Google's Brillo Weave, Apple Home Kit

IoT Interoperability Sandboxing

- Use Quest-V sandboxes to isolate IoTivity / Alljoyn software stacks
    - Promote secure isolation of networks of devices
- Use replicated / distributed monitor network to identify “unusual” (potentially malicious) network activity

What Next?

- Continue port of Quest(-V) to Edison and Minnowboard Max
- Develop 3D printer controller
  - Investigate techniques to quarantine and verify 3rd party service requests before processing
- Develop autonomous vehicle system
  - Look at real-time control in presence of injected faults
- Home automation prototype
  - Provide secure services for 3rd party plugins

Conclusions

- Quest-V uses one monitor per sandbox
  - Heightens security & safety
  - Monitors are small
    - Not needed for resource multiplexing
  - Can potentially exploit this to build new security models
    - Monitors like multiple system guards
- Chip-level distributed system
  - Real-time inter-sandbox communication
  - Isolation of 3rd party services

The Quest Team

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