Ongoing evolution of Linux x86 machine check handling

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What's a good error?

• User has to see it, of course
  – That can be surprisingly difficult
  – Also psychological barriers ("users don't read errors")

• High level classification
  – Software error versus hardware error
  – Don't want a hardware error reported as a kernel bug
  – Still have low level details for experts (ideally separated)

• Identify affected component
  – Do not require low level knowledge to process
  – Works out of the box

• How serious is the error?
  – Do not upset the user unnecessarily
Error sources

• Machine checks from the CPU
• NMI
• PCI-Express Advanced Error Handling (AER)
• Chipset
• ACPI4 (APEI)
• Drivers
  – SATA errors
  – Ethernet
  – ...

• Presentation only covers machine check errors from the CPU
  – This includes memory on modern systems
What is a machine check?

- Machine check is a hardware error reported by the CPU
  - Not a software problem!

- Hardware corrects most problems, but sometimes it can fail
  - Memory, Interconnect, Cache, Internal errors

- Uncorrected errors raise exceptions ("MCEs")
  - Better to stop than to continue with corrupted data
  - Otherwise the corrupted data could hit disk or give wrong results
  - If you aren't sure where it is, stop the machine ...

- Corrected errors are reported in the background
  - Either using a poll handler or with interrupts ("CMCI")
  - Didn't cause corruption (yet)
Why are machine checks important?

• They report memory errors on modern systems
  – Memory error rate scaling roughly with memory sizes
  – Memory sizes are increasing quickly
    – More cores need more memory
    – Virtualization needs a lot of memory
  – This also means more memory errors
  – So good error handling is important

• On large clusters, errors are common
  • What's uncommon on a single system
  • ... becomes common when you have a hundred of them
  • ... and even very rare events become common on thousands of systems

• In general, good error diagnosis is useful
  – If you ever searched manually for a bad DIMM ...
  – Saves time and hassle
MCE errors in practice today

- Error flows for uncorrected and corrected errors
- Assuming 64 bit or 2.6.31+ with CONFIG_X86_NEW_MCE
- Mcelog has to be installed

- Some of these flows are still somewhat clumsy
  - The future will be brighter, hopefully
Classic unrecoverable MCE error today

• System detects uncorrected error
  – Requires ECC for memory
  – Machine check exception happens

• Machine check handler collects error and prints it out
  – CPU x: Machine check exception ...

• System panics on unrecoverable error
  – On auto reboot (panic=30) can be logged after reboot on many systems
    – Available then decoded in /var/log/mcelog some time after boot
    – Trap: doesn't work with double reboot or with power switch
  – You will see the panic on the console (not in X) or on serial/netconsole
    – If you don't have auto reboot a logging console is very useful
    – Console output can be run through mcelog --ascii to decode

• Analyze error, based on decoded output
  – For example, map to DIMM (“Memory DIMM ID of error: ...”)
  – If common, take corrective action
Corrected error flow today

• A data bit flips
  – Hardware detects error, using checksum, and corrects it and reports event

• CMCI interrupt happens or poll timer picks it up
  – Kernel logs it to internal buffer accessible through /dev/mcelog
    • Note this buffer can overflow

• Mcelog picks it up
  – Either as cronjob or in daemon mode or as trigger
    – In cronjob mode up to 10 minutes delay, worst case with polling
  – Mcelog decodes
  – Logged in /var/log/mcelog or syslog

• Analysis of the log entry
  – Identify component
  – Take corrective action if common
Low level MCE handler improvements

• General overhaul after comprehensive audit
  – A lot of small improvements, too many to list

• Monarch support: synchronization over all CPUs
  – Collect errors from all CPUs
  – Synchronize all CPUs
  – Process the most serious error first to avoid data corruption
    – When the hardware didn't contain the error shut down

• Bank sharing
  – Handle shared machine check banks correctly

• Corrected Machine Check Interrupt Support (“CMCI”)

• Injector support for testing and a comprehensive test suite
MCA recovery

• New CPU feature in upcoming Nehalem-EX CPU

• Recovery from some memory uncorrected errors
  – For example, Patrol scrub memory error in the background
  – Required a lot of changes in the MCE handler to do reliable
  – When recovering it's much more important to handle all corner cases

• OS finds out what the corrupted page does
  – And attempts to get rid of it

• Machine check architecture has new status bits for recovery
  – Signalled, Action-Required
  – Different types of errors: Action-Optional, Action-Required, UCNA, Corrected
HWPoison handling in the VM

- VM finds out who owns a page and stops using it
  - Pages with copy on disk can be just dropped
  - Or application is killed, if data has no copy
  - IO error for dirty file cache pages
  - Free pages will be ignored on allocation

- Difficult because error can come in at any time
  - Can disrupt normal page livecycle
  - Error code has to be very careful
  - Also testing is difficult

- Put page on bad page list and never reuse it again
- Page table entry of any mappings is poisoned
- Early kill versus late kill mode
Virtualization

- Virtualization requires a lot of memory
- Many eggs in a single basket ("servers on a single machine")
- Error handling and error containment is important
  - If there's a problem only kill single guest, not all

- KVM guests act like processes
  - So uses the per process infrastructure in standard hwpoison

- Uncorrected recoverable errors can be forwarded to a guest
  - Guest can inject the error as machine check (or KVM kills)
  - Guest with MCA recovery support can recover (or panic)

- Similar code developed for Xen
  - No forwarding for Xen currently
Memory error application interface

- Applications can catch memory errors, which are signals
  - Was needed for KVM, but can be used by others too
- Applications have often cache, which they can drop
- Expect only a few specialized applications to use it
- SIGBUS with an address can be caught
  - BUS_MCEERR_AO  Action-Optional error in process
    - Get rid of page specified by si_addr, si_addr_lsb
    - Take out of free list or similar
  - BUS_MCEERR_AR  Action-Required error in current execution context
    - Need to abort right now (siglongjmp etc.)
- Prctl to set early kill vs late kill for the process
  - Late kill is typically better for error aware applications
Mcelog

• User space backend that decodes and processes MCE errors
  – Also identifies components with some firmware help

• Traditionally on 64 bit x86, now on 32 bit too

• Traditionally cronjob every 5 minutes, future daemon
  – Daemon mode allows to keep state about errors in memory with query interface and triggers
  – Some old attempts using an on-disk database proved difficult

• Can run shell scripts on specific events (“triggers”)
  – Notify administrator, offline component, ...

• Long term goal: high level errors in syslog
  – Some steps into this direction
Error accounting

• Possible in mcelog daemon mode

• Often most interesting is which component the error affects
  – DIMM, memory, PCI card, etc.
  – To see trends and replace the right component quickly if needed

• Individual errors are often not that interesting
  – Errors often come in bursts and individual errors in a burst are not interesting
  – Large clusters can generate a lot of data, which is difficult to process

• Mcelog moving towards accounting errors per component
  – Only reports “n errors in last x hours on component k”
  – Triggers when thresholds are exceeded
  – Discovers component names with firmware help
  – Can disable individual error logging for less data
Open issues

• Crashdump handling

• More testing is always useful
  – Stress test suite under way
  – Any contributions welcome

• Better error reporting in general
  – More high level errors better presented

• More error sources in mcelog

• Intelligent error handling in mcelog
  – If you have ideas, feel free to contact me
Resources

- **http://halobates.de/mce.pdf**
  - Old paper about Linux machine checks

  - Description of the x86 Machine check architecture

- **git://git.kernel.org/pub/scm/linux/kernel/git/ak/linux-mce-2.6**
  - MCE development tree (hwpoison, mce4)

- **git://git.kernel.org/pub/scm/utils/cpu/mcelog.git**
  - Mcelog development repository

- **ftp://ftp.kernel.org/pub/linux/utils/cpu/mce/**
  - Mcelog releases

- **git://git.kernel.org/pub/scm/utils/cpu/mce-test.git**
  - MCE test suite (or now part of LTP to [http://ltp.sourceforge.net](http://ltp.sourceforge.net))

- **git://git.kernel.org/pub/scm/utils/cpu/mce-inject.git**
  - MCE injector
Mcelog versus EDAC

- EDAC old style driver for chipset memory controllers
  - Exposes a lot of low level details
  - New model: memory controller in CPU
  - Memory errors integrated with machine checks
  - Handled by standard MCE subsystem

- EDAC needs driver for each platform
  - And often accesses “non stable” registers that could change even with steppings
  - Mcelog uses standardized interfaces

- No integration with software
  - Requires special configuration for each board to identify components

- Cannot do a lot of things that user space (mcelog) can do
Testing

• Testing machine checks is difficult
  – Normal operation doesn't have enough errors
  – So standard Linux community testing model doesn't work very
  – Needs special injection support and test suites

• Various injectors on software level (without hardware support)
  – Low level machine check injector
  – Page error injector for process and for arbitrary page

• New injectors, test suite mce-test for testing MCEs
  – Testing low level handler with mce-inject
  – Testing hwpoison VM code in process context
    – Bring pages into specific states and test to see if they can be poisoned

• Ongoing work to get the best test coverage
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