Software Engineering at VMware

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vmware

The Challenge

- Suppose that you have a very popular software platform:
  - … that includes hardware-level and OS code that can easily crash a machine
  - … that must run on many different hardware platforms
  - … that big corporations use all the time and must be very reliable
  - … that customers really like and constantly want new features for
- How do you do very rapid development of large new features and yet produce high-quality releases
  - Requires concurrent development via many developers
  - But can you really do high-quality releases with such concurrent development?

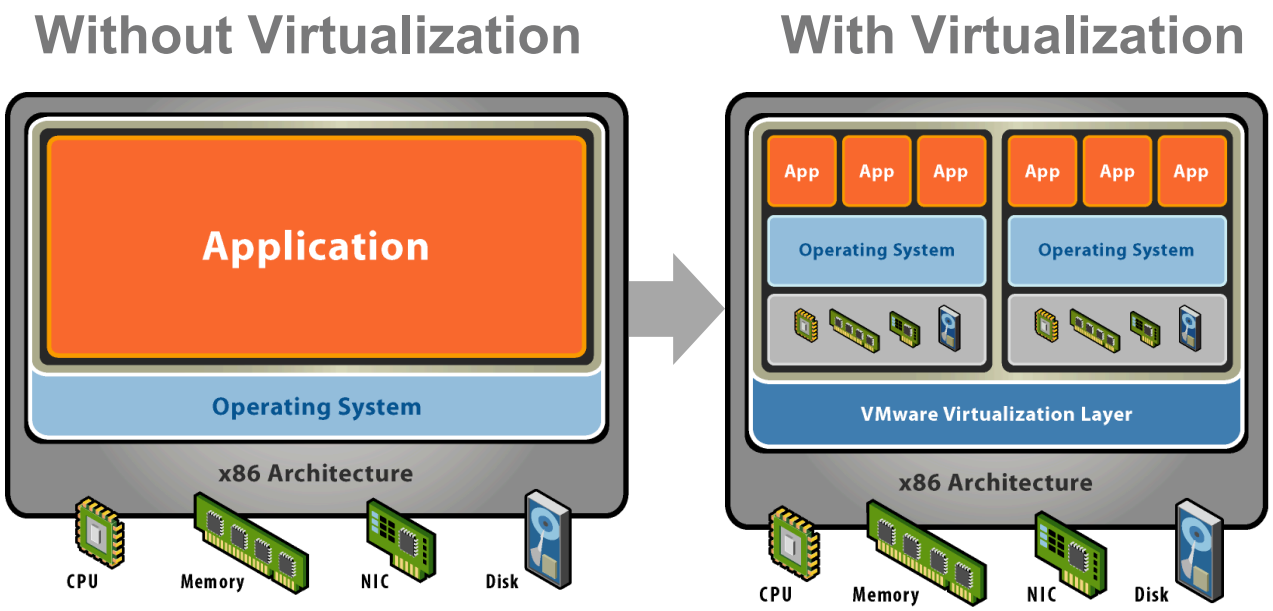
The Challenge (cont.)

- Big part of the solution:
  - Good developers
  - Coding practices that allow lots of testing while code is running
  - Reliable (and fast!) tools for building, testing, and merging code
  - Constant automated QA (testing)

Outline

- Background on VMware
- Scale of development and releases at VMware, and some of our problems
  - Rapid concurrent development
  - Rapidly evolving interfaces
  - Many product releases sharing same code
  - Many hardware platforms
- Some software techniques for keeping OS reliable
- Some more automated techniques for keeping code base robust and ensuring quality of releases

What is Virtualization?



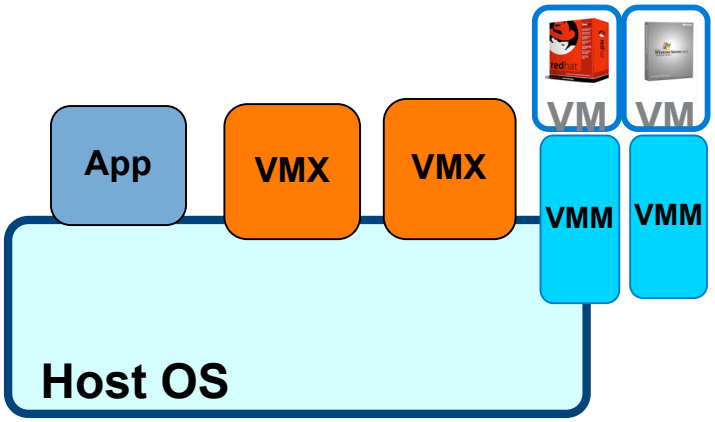
- VMware provides hardware virtualization that presents a complete x86 platform to the virtual machine
- Allows multiple applications to run in isolation within virtual machines on the same physical machine
- Virtualization provides direct access to the hardware resources to give you much greater performance than software emulation

Why are virtual machines useful

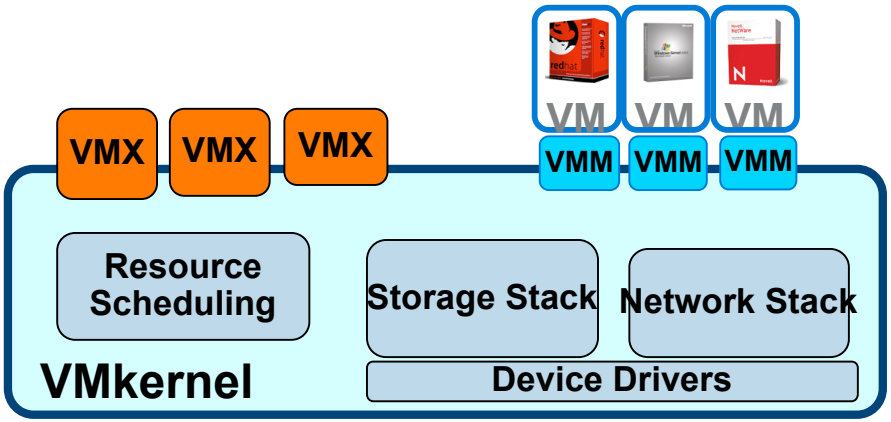
- Run Windows on Linux (or Mac OS)
- Consolidate many different workloads/guest OSes on one big machine (“server consolidation”)
- We can migrate running virtual machines (VMs) run one host to another, so we can do automatic workload balancing across a cluster of machines
- VMs also simplify high availability, disaster recovery, etc.

VMware Virtualization Architectures

VMware Workstation



VMware ESX Server



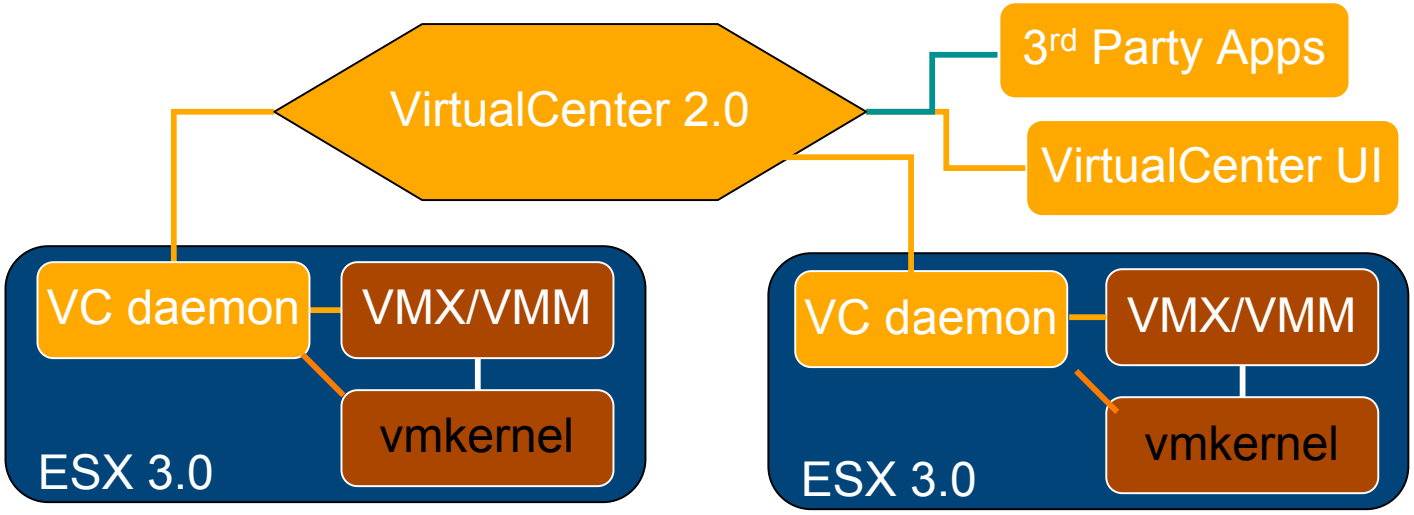
Hosted design

- Runs on Windows, Linux, MacOS
- Device support is inherited from host operating system
- Virtualization installs like an application rather than like an operating system

Hypervisor

- Virtualization supported via small kernel (VMkernel)
- Highly efficient direct I/O pass-through architecture for network and disk
- Excellent management/scheduling of hardware resources

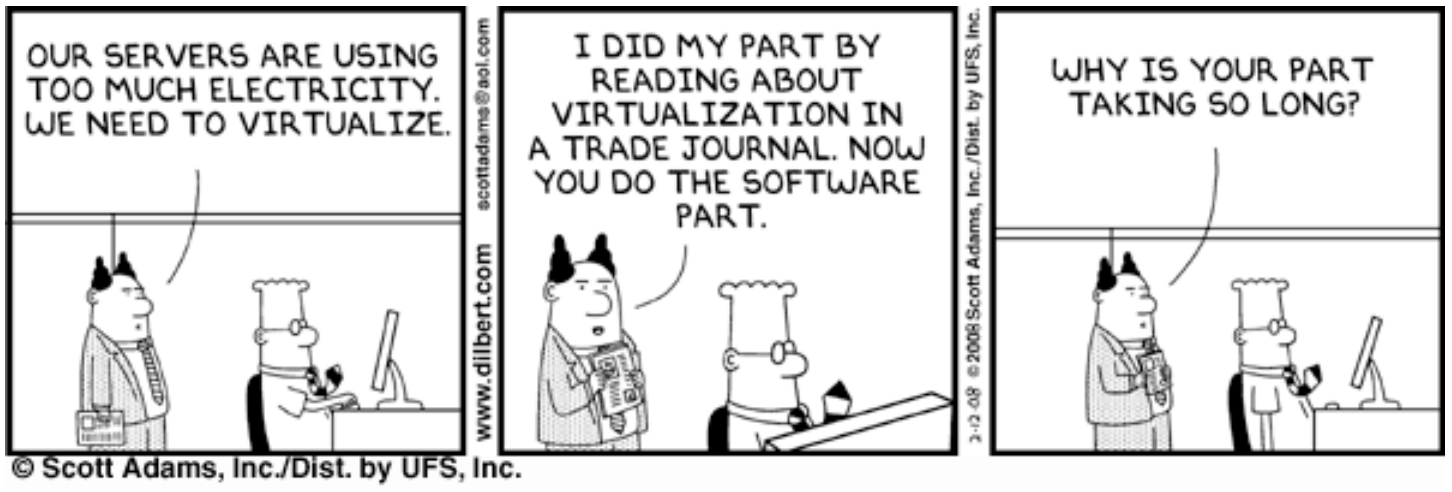
Virtual Machine Management



- We touch every level of the software stack – drivers, CPU code, OS code, user-level code, UI, management agents, management applications
- We keep adding features that can span the entire stack
- Strong interfaces – management API and DDK
- Most intertwined code – VMX, VMM, and vmkernel

Customers constantly want new features

- 64-bit support
- 10-Gigabit ethernet
- Support for new features in Intel/AMD chips (including virtualization support)
- NUMA support
- Storage migration
- Network boot
- …..



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Goal

- Goal: fast development of new features and support for new platforms while maintaining performance and reliability
- Problems:
  - Highly concurrent development
  - Rapidly evolving interfaces
  - Frequent and concurrent releases
  - Many hardware platforms

Highly concurrent development

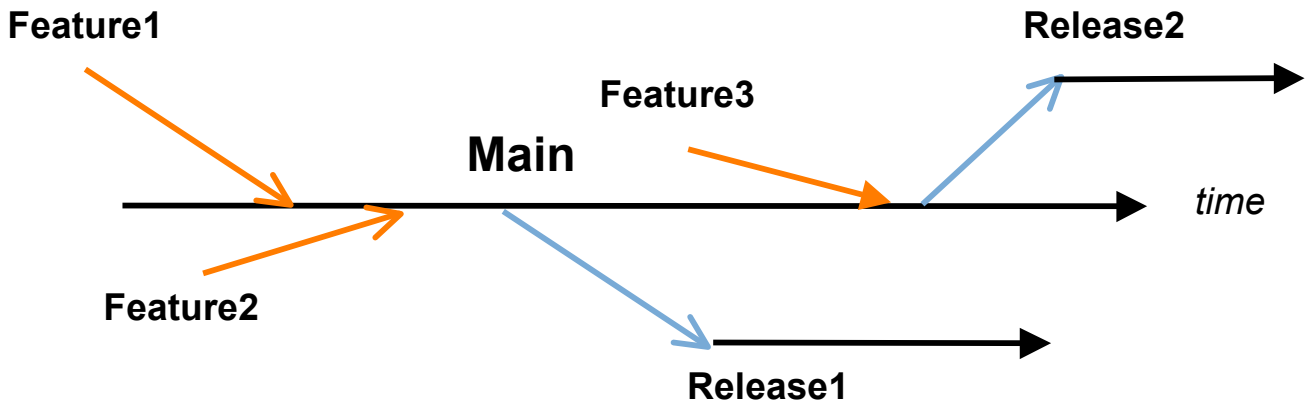
- Biggest areas of inter-dependence: vmkernel, VMX, and VMM
  - Largely written in C
- Recently, for the vmkernel (hypervisor):
  - 15-19 checkins per day
  - 150 developers
- For the vmkernel, vmx, and vmm:
  - 36 checkins per day
  - 230 developers
- Need to minimize problems with checkins, so one checkin with issues doesn't affect lots of developers

Many releases

- VMware Workstation, VMware Server, and ESX Server that are released independently
- All share common code (VMX and VMM)
- Many different platforms:
  - Windows
  - Linux
  - MacOS
  - VMkernel
    - variety of server hardware
    - Variety of storage hardware (SCSI, FibreChannel, iSCSI, NFS) and network hardware (1 Gb Ethernet, 10 Gb Ethernet, TCP offload, …)
  - 32-bit vs. 64-bit

Concurrent Development and Releases

- You need to integrate a variety of features and bug fixes into the code base (**Main**)
- You need to create stable snapshots of the source code for product release
  - Typically, you create branches of the code for product releases, so development for future releases can continue on Main
  - Code will have to be “cross-ported” from product branch to Main



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Software development for vmkernel

- Mostly written in C
- Includes base kernel, ~40 drivers, ~25 other modules
- Modules do things such as:
  - Virtual switch
  - Storage multipathing
  - VM migration
  - Distributed file system (VMFS)
- Important to continually verify that new features/sub-systems will work together

Static Checking

- Maintain the strictest possible static checking, so we check “easy” bugs as soon as possible
  - Important to do from the start, else it becomes hard to fix later
  - E.g. all those warning messages that come from linux drivers….
- We use the strictest type checking options from the compiler
  - Sometimes use C++ compiler, since it does stricter checking
  - Catch 64-bit VMotion bug
- Coverity is very useful

Verify/test code while running

- Make it easy to enable/disable the verification code
  - Development and release builds, all extra code disappears in release builds
- Assertions are crucial
  - Simple and very general assertions are invaluable – e.g. don't ever block while you have a spin lock or in ISR
  - Document and verify invariants at beginning of functions – e.g. the scheduling lock must be held
  - Allows a module/function to protect against a drastic change in its usage
  - Catch compiler and processor bugs!
    - Page table change (CR3) doesn't immediately take effect

Verify/test code while running (cont.)

- Lock ranking
  - Establish global order for all locks, locks must be acquired in that order to guarantee no deadlock
  - E.g. buffer cache lock must always be acquired before file system lock
  - Extra benefit – discourages modules from creating too many locks

- Stress options
  - Used for causing unusual, but recoverable conditions

```
if  (STRESS_OPTION(disk_error))   return DISK_FAILURE;
```

  - Enabled in devel builds, returns TRUE in (say) 1 out of 1000 calls
  - Allows testing of cases that would be very hard for QA to reproduce

Verify/test code while running (cont.)

- POST (Power-on self test)
  - Tests that run when module is initialized
  - Hard to get developers to write them
- Heap memory poisoning

Modularity

- Make it more likely that one module can't affect another
- Resource usage – verify that a bottom-half or kernel thread doesn't run for more than reasonable limit
  - Can lead to very mysterious networking performance…. (serial port bug)
- Separate heap for each module
  - So memory bug with one module is less likely to affect another

Modularity (cont.)

- Verify DMA is to appropriate memory
  - DMA goes around MMU, can write arbitrary memory
  - IO MMUs are coming
- Use address-space protection
  - Add extra address space protections in devel builds
  - Separate address space for drivers (Nooks work)
  - Move code out to user space

Miscellaneous

- Coding conventions
- Get error codes right from the start
  - Don’t use 0 and –1!
  - Even Linux error codes don’t carry enough information
  - Want more general error codes that carry arbitrary other information
  - Probably want requirement to never ignore error codes
- Interestingly, many of these kernel issues apply to other multi-threaded, modular applications:
  - Hostd – multi-threaded management daemon on ESX host
  - Web-servers
  - App servers

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Large-scale Concurrent Development

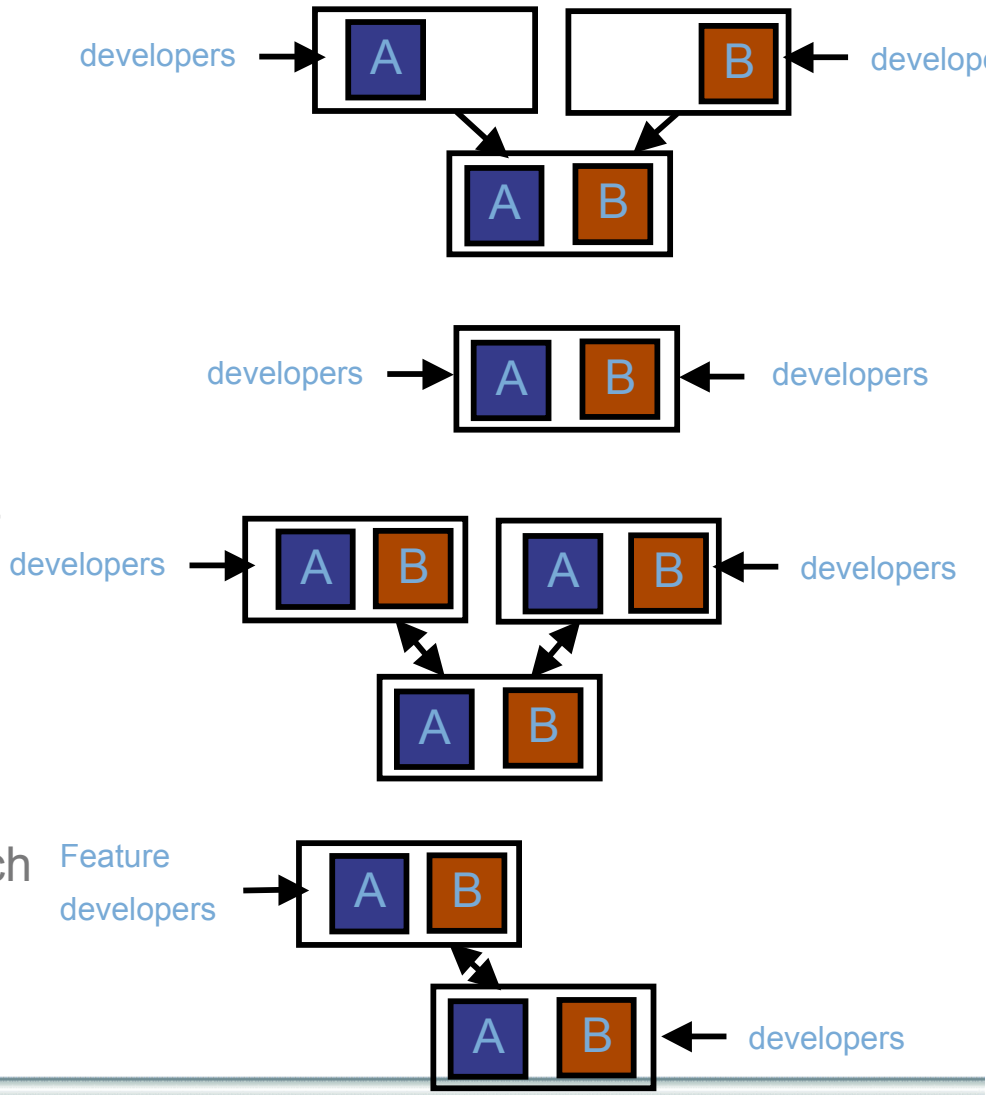
- How do you keep source code base (Main) stable for developers and product releases?

➔

- Make it easy to test/verify code while running
- Good developers who are careful and follow responsibilities
  - Code reviews
  - Pre-checkin build
  - Pre-checkin testing
- Policy for determining how code is integrated into Main

Concurrent development

- Modular code with well-defined interfaces
  - develop in separate branches and merge
- Most changes span modules and interfaces always changing
  - free-for-all!
- Most changes confined to modules, but interfaces change – "component branching"
  - More stable than free-for-all
  - Requires sync back-and-forth
- Some features are huge and touch every part of the system:
  - major features developed on "feature branch"



What to use?

- Feature branches are painful
  - Because you must always merge with changes from other developers until you are ready to check in
  - But useful for really big features that can be incrementally added
- VMware uses component branching
  - Requires merging between the component branches
  - Most other OSes seem to do this as well (Microsoft, Linux, have hierarchy of branches with human mergers)
  - Big changes may use feature branch
- Component branching requires frequent sync'ing between branches after really good testing

Fast automation is key!

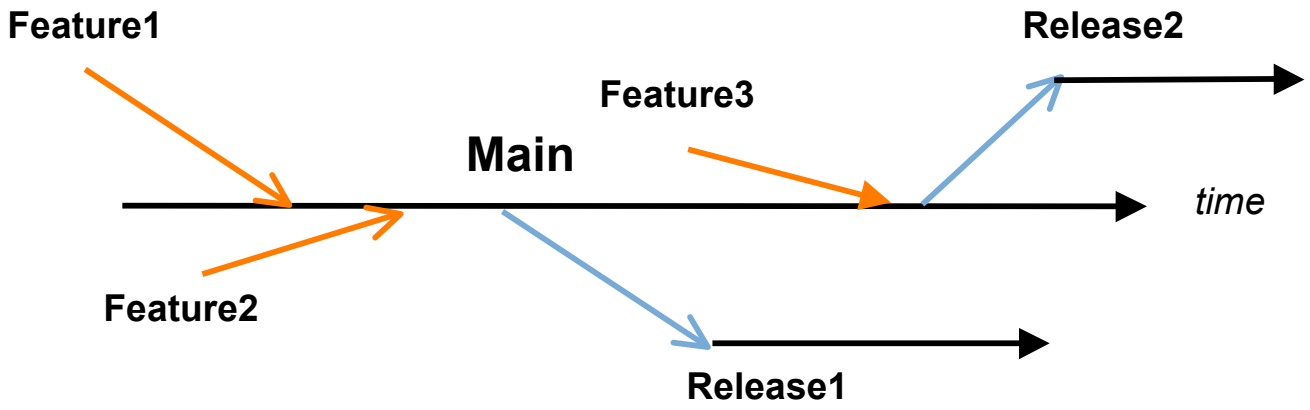
- We need to be able to do automated testing
  - We have many levels of automatic tests: pre-checkin, nightly tests, longer tests before merging between branches…..
- We need automatic merging of code from one branch to another
  - Alternatively, have a “gatekeeper” that manually does merge, verifies functionality – e.g. Linux integration trees
- For all this, we need a very fast build system
  - So developers will build on all possible platforms before checking in
  - So we can verify checkins to branches, merges to other branches very quick
  - So we can quickly check if checked-in code compiles on all platforms

Concurrent Development

- Problem: rapid concurrent development of code with rapidly changing interfaces
- Solutions:
  - Developer responsibilities, including pre-checkin tests
  - Component branching
  - Automated build of tree after checkin
  - Automated test of build after checkin
  - Should we have automatic backout if build or tests fail? Must be quick to isolate exact change that caused problem….
  - Continous manual and automated QA to find bugs early….

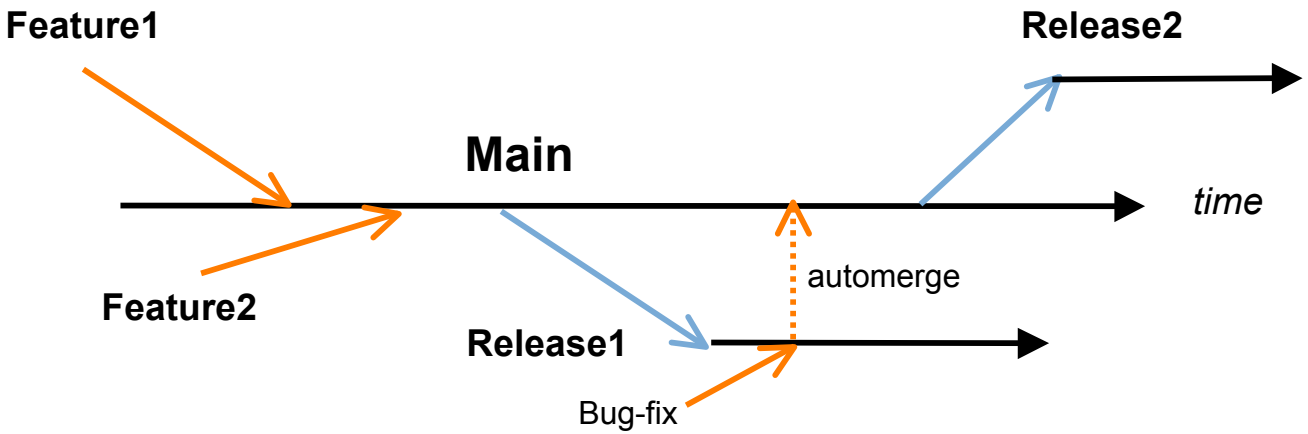
Concurrent releases

- Problem: releases of many products on many platforms
- Solutions
  - Build all products on all branches in order to catch problems early
  - Create “product branches” when nearing release of a product



Concurrent Releases (cont.)

- Product branches automatically merge changes to main development tree
  - Need to do continuous builds on main tree to check for problem because of automerges
  - Need to remind developers if automerges fail
  - Should really do merging via human



Conclusion

- Rapid development of new features on a large code base that is changing at all layers is hard!
- Solutions:
  - Good developers with good development practices
  - Coding practices that allow lots of testing while code is running
  - Reliable (and fast!) tools for building, testing, and merging code
  - Continuous testing (manual and automated)
- Developers are important, but a good build/tools team is also crucial