CONTINUOUS INTEGRATION AND TESTING OF A YOCTO PROJECT BASED AUTOMOTIVE HEAD UNIT

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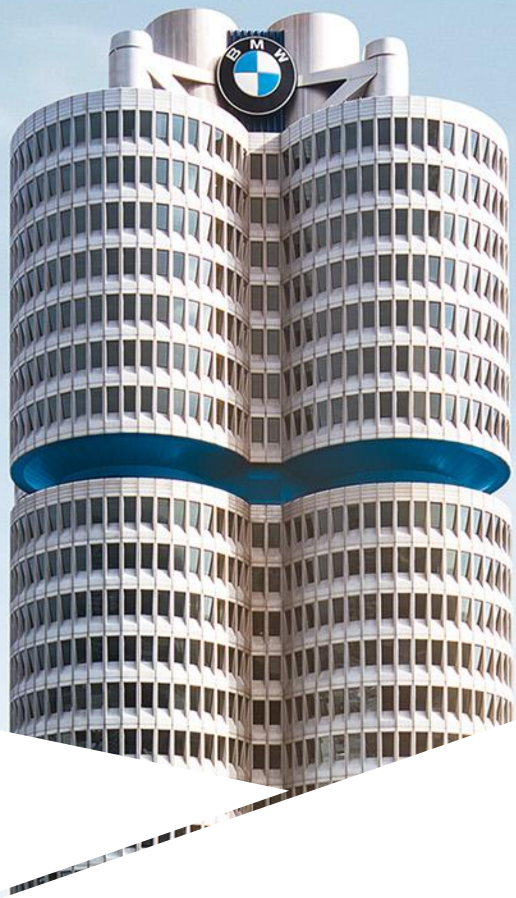


Embedded Linux Conference Europe 2016

BMW GROUP

THE NEXT 100 YEARS

ABOUT BMW CAR IT GMBH

- Founded in 2001 as a wholly owned subsidiary of the BMW AG
- Strengthen BMW's software competence
  - View vehicles as software systems
  - Develop innovative software for future BMW Group vehicles
  - Prototype solutions for early and reliable project decisions
- Participate in several open-source communities and research projects

CARS AND HEAD UNITS

PROJECT SETUP

- Development of a head unit for BMW cars
  - A connected multimedia computer with navigation and telephony
- Several companies, physically distributed
- Hundreds of developers, on various levels
- Complex infrastructure
- Technical and political obstacles to set up technical solutions

CI SYSTEM REQUIREMENTS

- Provide fast feedback for developers, integrators, project organization
- Automatic multi-stage CI
- Software components change-verification in an SDK environment
  - Build components
  - Execute unit tests
- Software integration change-verification in the system build
  - Build the full system, for all targets, all images
  - Quality assurance checks after build
  - Build Acceptance Testing (BAT) on real target environments (hardware, SDK)

QUICK OVERVIEW OF YOCTO PROJECT

- Linux-based cross-compilation framework
- Set of metadata and a task scheduler which, combined, can be used to build software
  - Metadata
    - Configuration files. Examples:
      - Machine configuration (target platform)
      - Target Linux distribution configuration
    - Recipes
      - Specification of tasks on how to build software (fetch, configure, compile, package etc.)
      - References (e.g., git URL and commit id) the actual source code of the component it describes
      - Tasks can be implemented in Python or Shell scripts
      - Maintained in separate meta repositories (e.g., git repository)

QUICK OVERVIEW OF YOCTO PROJECT (CONTINUED)

- Task scheduler: BitBake
  - Inputs: metadata
  - Outputs (typical use): packages, images, toolchains, SDKs etc.
- Sysroots
  - Global staging area for builds
  - Where build dependencies are installed during build
  - Shared among all build tasks
- Caching
  - Shared State cache (sstate cache)
    - Cache of processed BitBake tasks
  - Download cache
    - Cache of source code (git, subversion, tarballs etc.) downloaded by BitBake

YOCTO PROJECT: NEAT FEATURES AND CHARACTERISTICS

- Very flexible
  - Fine-grained control on artifacts
  - Compile-time configuration
- Extensible
  - It's easy to add your own metadata or extend existing ones by adding layers
- License tracking
  - You can specify what licenses your product cannot ship
- Support
  - Commercial support
  - Community support
- QA checks
    - Help to catch problems earlier

SOURCE CODE MANAGEMENT

SOFTWARE COMPONENTS

- Public open source (git, tarballs, etc.)
- Internal projects (git)
- Binary software deliveries from suppliers (subversion)

SYSTEM COMPONENTS

- Yocto Project (git)
- Open source meta layers (git)
- Proprietary meta layers (git)
- All system components are git repositories assembled as git submodules in a single base git repository
  - Each commit in the base repository represents the full state of all the git repositories
  - Testing changes that affect multiple submodules is easy (e.g., Yocto Project updates)
  - Drawbacks
    - Confusing for developers new to git
    - Adding and removing submodules cannot be easily tested in CI
    - Not nicely integrated to Gerrit, Gitweb or git GUI tools
  - Alternatives
    - Repo
    - Custom scripts that save state somewhere

GERRIT

- Hosts git repositories for software and system components
- Topics to group commits that affect multiple repositories
- Custom tool to check out topics into a working tree (python, gerrit API’s)
- CI jobs can verify all changes with the same topic
- Positive aspect: for experienced developers this setup works well (local feature branch == topic)
- Drawbacks
  - Inexperienced developers make mistakes
  - Mixing unrelated changes in a single git repository, under the same topic
  - Trying to merge commits that are not part of the same branch
  - Gerrit UI is confusing
  - Corporate IT hosted Gerrit is not up-to-date with upstream Gerrit
- Alternatives
  - Patchwork/e-mail
    - E-mail is a nightmare in corporate environments (Outlook, MS Exchange, HTML, Windows users etc.)
  - Github, Gitlab (we haven't tried them)

SOURCE CODE CHANGE INTEGRATION

- In the software component we apply changes with Gerrit (apply and merge)
- In the system integration we create pull requests that involve multiple git repositories
  - e.g., a Gerrit topic that contains changes in multiple repositories
  - Pull requests are called Integration Requests (IR) in our process
  - Integration requests can only be issued after a positive peer review in Gerrit and successful verification build in CI
  - CI system merges and tests the merged changes before release

OVERVIEW OF THE CI PIPELINE

SOFTWARE COMPONENT DEVELOPMENT

- Software component developers work with the SDK
- Push changes to Gerrit code review
- Gerrit triggers a verification build with the SDK (includes unit tests)
- In case of successful verification, changes can be merged automatically or manually

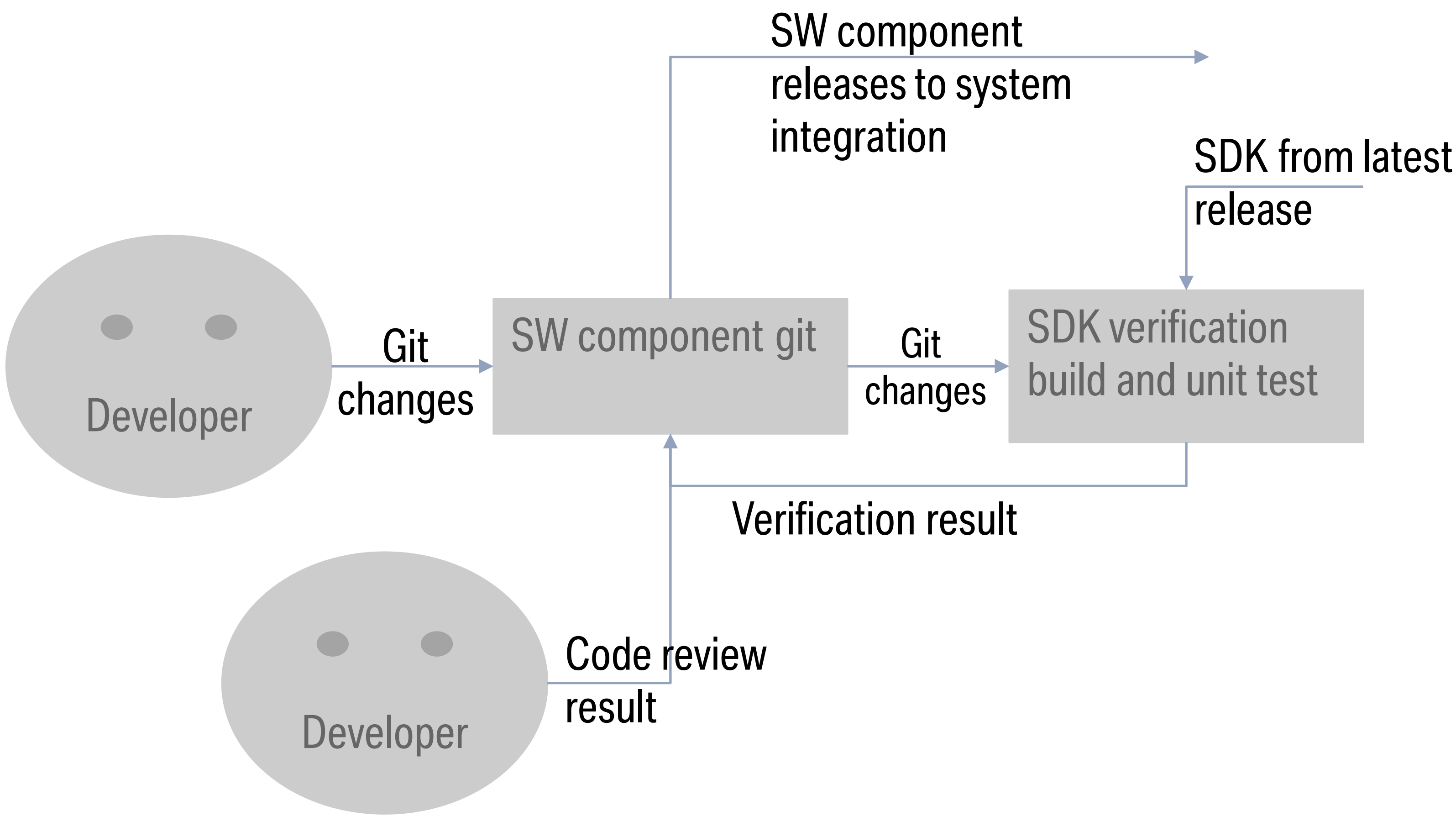
SYSTEM INTEGRATION

- Two types of integration requests
  - Automatically/manually submitted from a component repository
    - The git commit hash in a BitBake recipe is changed
  - System integration Gerrit topic affecting multiple git repositories

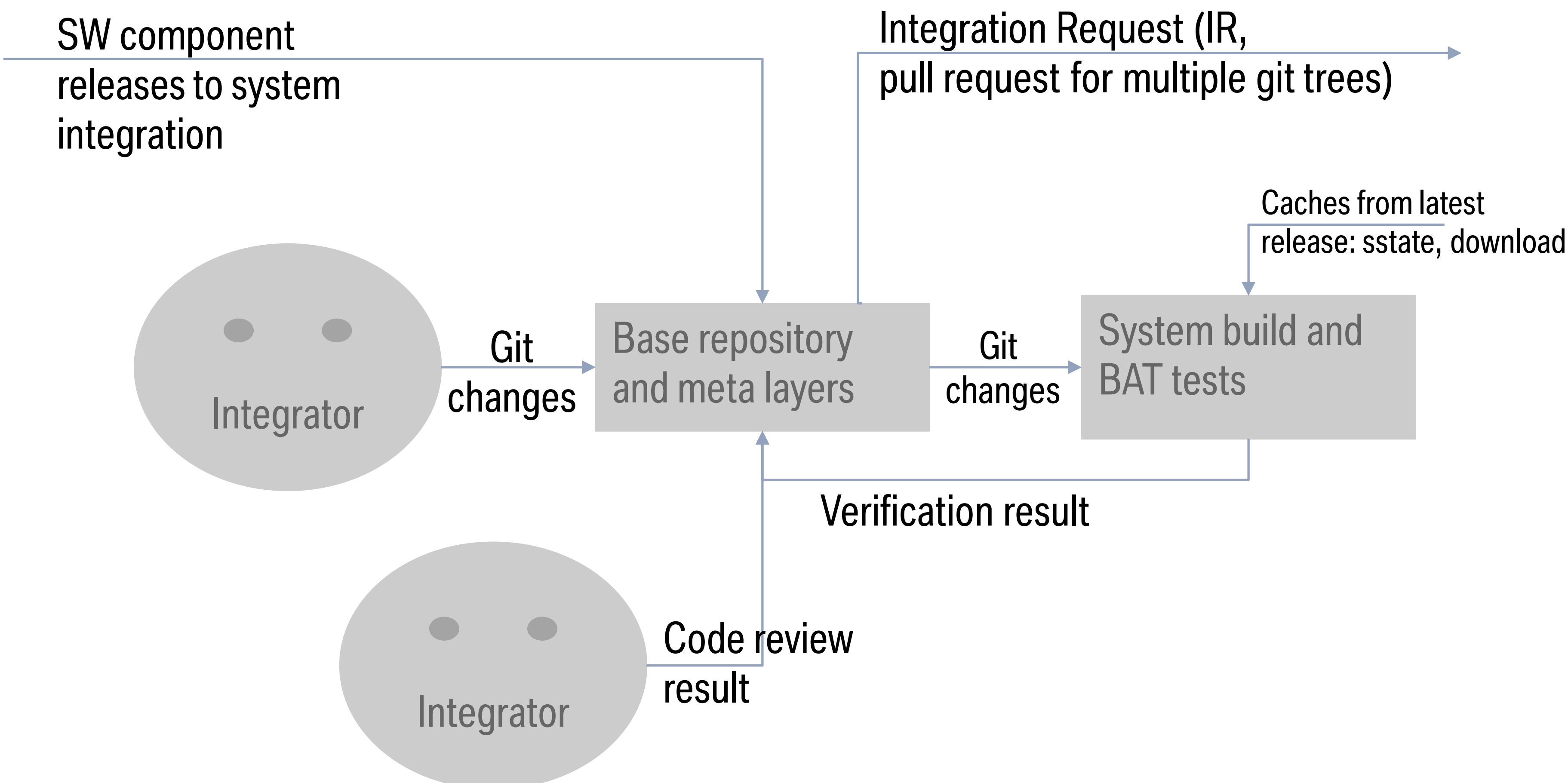
MULTI-STAGE CI

– SDK verification
– System build
– Merge verification before release

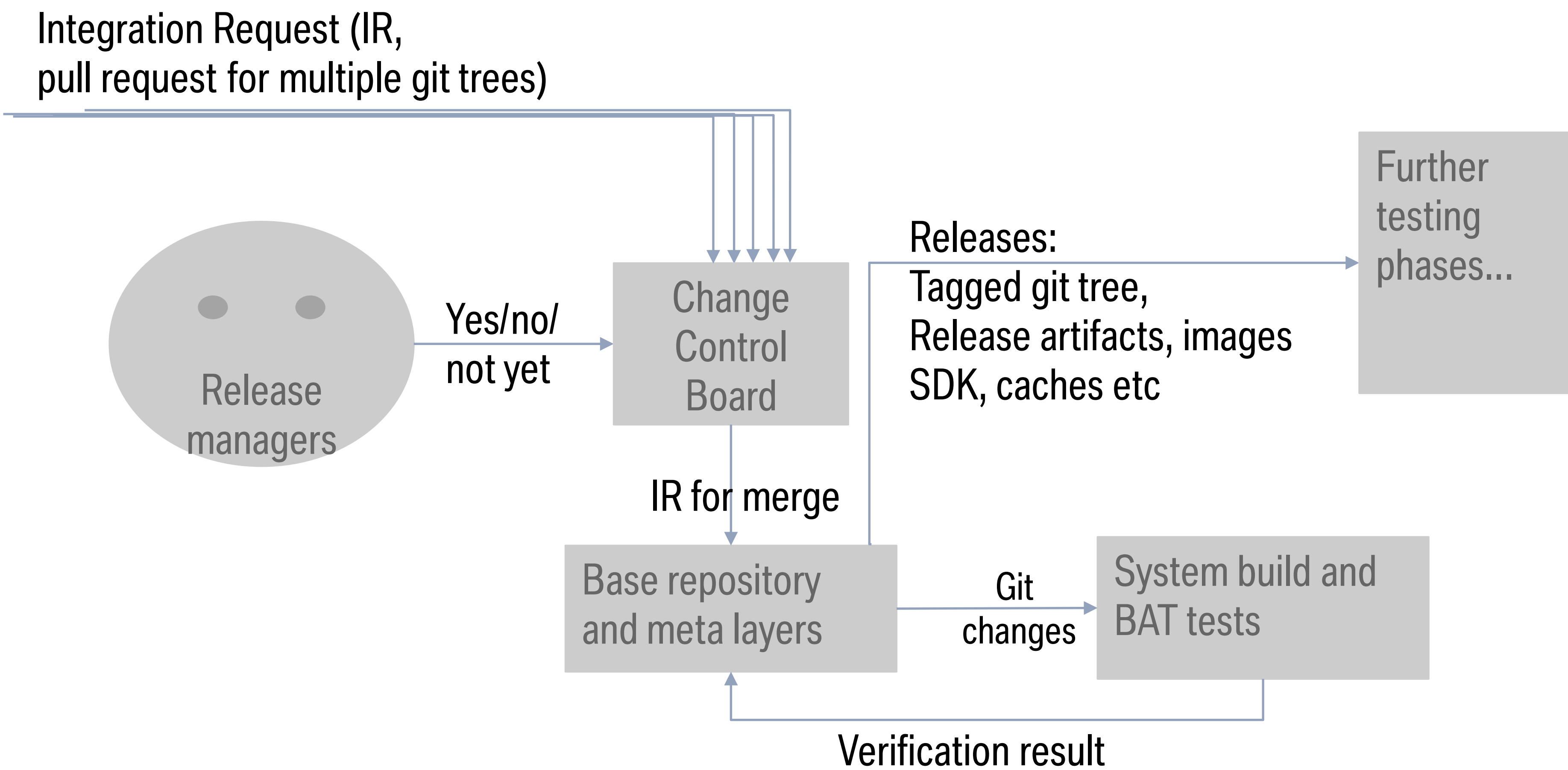
SDK VERIFICATION FOR SW COMPONENTS



SYSTEM CHANGE VERIFICATION



SYSTEM RELEASES



AUTOMATIC RELEASE MANAGEMENT

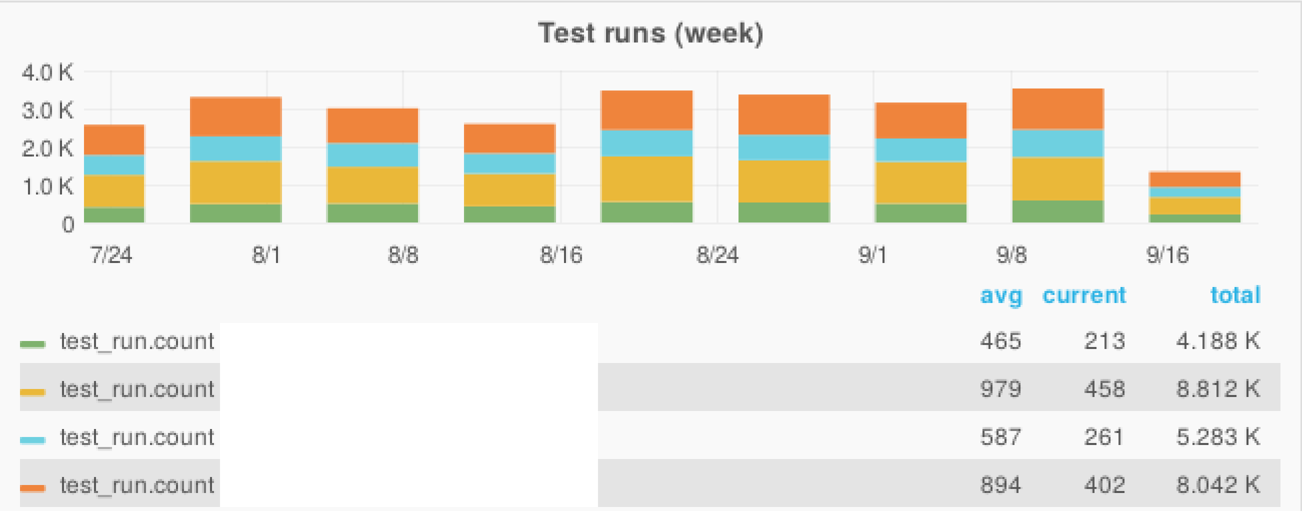
– Integration requests are applied and tested in a full system build
– Change Control Board can control which integration requests get merged
– A set of integration requests are collected and pushed out as a release
– New releases can be created manually or based on timer

CI INFRASTRUCTURE

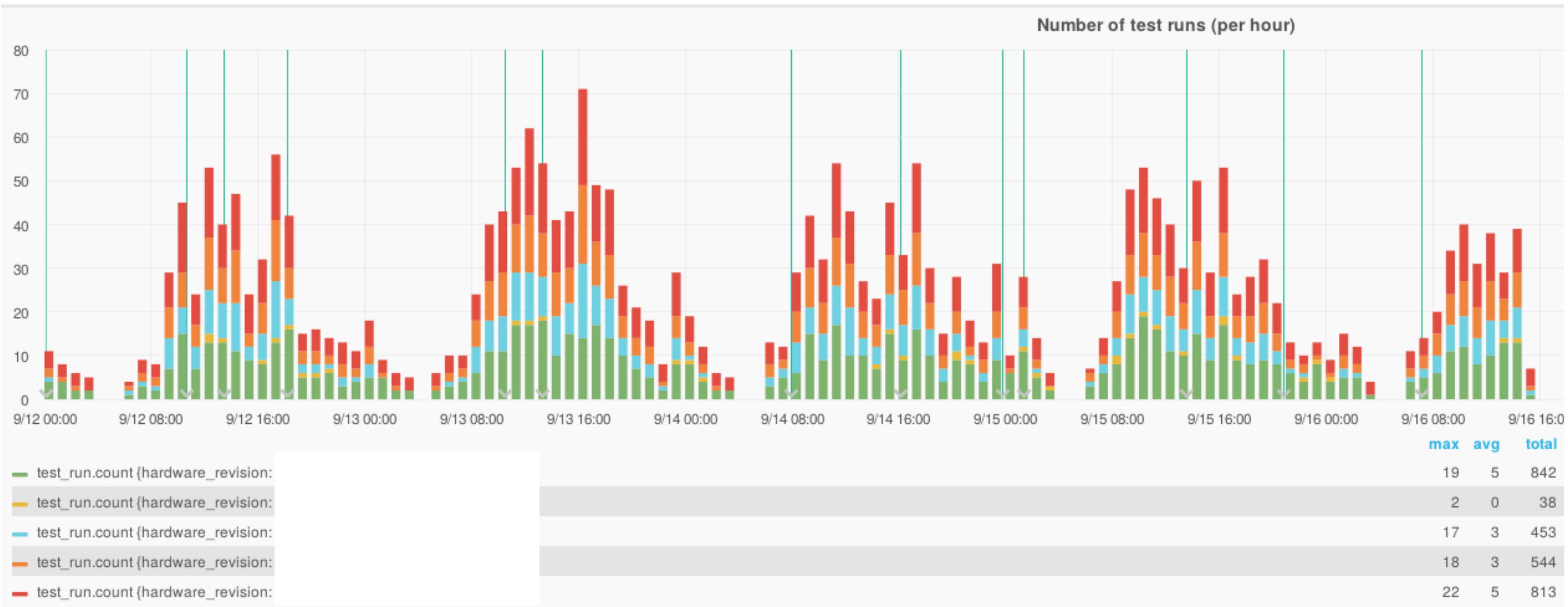
- Gerrit, git and subversion servers
- Jenkins servers (several masters and even more slaves)
  - Predominantly virtual machines
  - Build slaves (SDK and BitBake builds)
  - SDK build slaves: 45 (8 CPUs, 20GB of RAM)
  - BitBake build slaves: 36 (16 CPUs, 64GB of RAM)
    - Two bare metal machines (no virtualization): 40 CPUs, 128GB of RAM
    - One daily build from scratch (without sstate cache)
- File and cache servers
- Database server
- Cluster of virtual machines
- Bug and issue tracking servers

- Test farm with special hardware, including target hardware devices
  - Jenkins masters have test jobs which are triggered by build jobs
  - Custom Python-based test farm framework uses RabbitMQ to trigger test executions on the test farm
  - Test farm has 16 SDK, 20 virtual targets and 12 real target executors
  - Besides the test farm we also have automated tests for the build artifacts
    - Test as much as possible without the target platforms

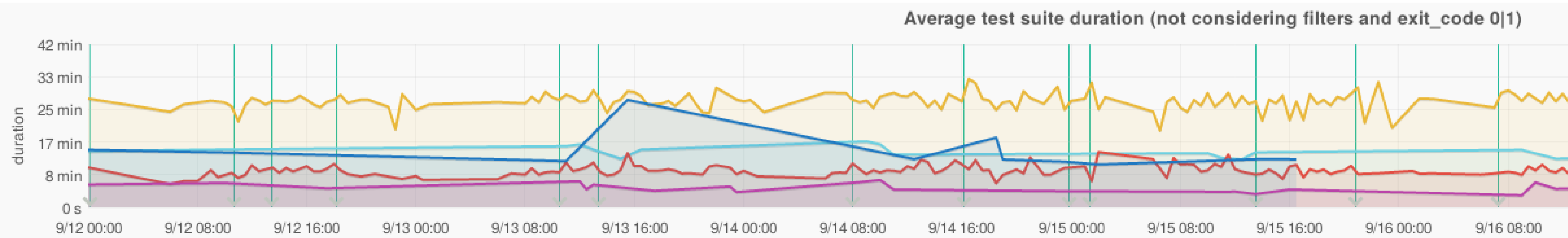
TEST FARM STATISTICS (1)



TEST FARM STATISTICS (2)



TEST FARM STATISTICS (3)



	max	avg	current
test_run.mean {hardware_revision:	14.5 min	13.8 min	12.8 min
test_run.mean {hardware_revision:	37.3 min	26.9 min	29.6 min
test_run.mean {hardware_revision:	22.7 min	14.8 min	13.6 min
test_run.mean {hardware_revision:	21.1 min	20.4 min	19.8 min
test_run.mean {hardware_revision:	18.3 min	8.3 min	9.1 min
test_run.mean {hardware_revision:	27.4 min	13.1 min	12.3 min
test_run.mean {hardware_revision:	12.6 min	5.0 min	2.9 min

LESSONS LEARNED

- Keep it simple
- Solid foundations
  - Use real distributed system technologies, not hacks on top of Jenkins and regular file transfer tools
- Corporate networks are sometimes less reliable than Internet services
- Automate everything (ansible, puppet etc.)
- Virtualization is not an ideal solution when it comes to performance

LESSONS LEARNED (CONTINUED)

- Positive aspects
  - It works, although sometimes administering the system is painful
  - It fulfils the requirements of the project as a CI system
- Negative aspects
  - Jenkins is not a distributed system
  - Not everything is automated
  - Some changes in the CI infrastructure cannot be tested by the CI system

BUILDS

SOFTWARE COMPONENT BUILDS

– Use the SDK provided by BitBake builds
– SDK can be extended with packages, automatically in CI jobs, or manually by users
– ccache is used to make builds faster

SYSTEM BUILD

- Runs inside a LXC container with Ubuntu 14.04
- The container
  - Provides build isolation
  - Can be constructed during build (e.g., container changes can be tested in the CI)
  - Mitigates host contamination
    - Prevents system components to leak into the build environment
  - The influence of the host system in the build is at least reproducible
  - Container changes can be deployed faster than changes in the infrastructure
  - Developers are free to use any Linux distro they want and still use the container for building

SYSTEM BUILD - IMPLEMENTATION

- Wrapper shell script around BitBake, for each target machine
  - In CI builds, synchronizes the sstate cache from the previous release before calling BitBake
  - In CI builds, used a mounted NFS share for the download cache
  - Developers are out of luck with regard to caches, due to network setup complexity
  - Lesson learned
    - Bash and `set -eux -o pipefail`, at least
    - Cleanup in `trap` commands

SYSTEM BUILD – META LAYERS

- Each meta layer is a single git repository with a single owner (a team)
- The owner has +2 review rights for its git repository
  - A change gets approved if it gets a +2 from review and a +1 from the verification build
- More than 60 meta layers
- More than 2800 recipes
- More than 400 bbappends

SYSTEM BUILD – BITBAKE CONFIGURATION

- template file for `local.conf`
- sed magic for environment-dependent configuration options (e.g., mirrors and network usage metrics)
- custom script for setting BitBake parallelization options based on the number of CPU cores and RAM (details later)

SYSTEM BUILD – BITBAKE ALL

- "`all`" is a special BitBake recipe that specifies everything to build
- Multiple images for the target hardware ("boot modes")
  - Image artifacts include flashing and testing tools
  - Images are tarballs, not filesystem images (flashing creates filesystems)
  - Building an image is a serial operation (cannot be parallelized)
  - Multiple images can be build in parallel, but not the installation of packages in a single image
  - Images share a lot of content, but we don't have a way to reuse the common parts
  - The target images have big data blobs that we manage with git annex (plugged into BitBake)
  - Image tarballs are compressed with `pigz` for parallel compression (using multiple CPUs)
  - Support for filesystem extended attributes is needed in the future

SYSTEM BUILD - SDK

- Custom SDK instead of Yocto Project upstream
  - In the SDK we mix target and nativesdk packages, in a way that it is transparent for users
  - Motivation
    - Developers struggled with the cross toolchain and cross environment setup
      - Mistakes in the development of components' build system (CMake)
    - Complexity of the cross-compilation environment shifted from developers to the integration team
- SDK content decoupled from images
- Custom namespace tooling instead of plain chroot (execution environment for the SDK, without root access)
  - Transparent cross-compilation in the SDK, using gcc, make, autotools, cmake and other tools from `$PATH`
  - From users perspective, it looks like a lightweight chroot

SYSTEM BUILD – SDK (CONTINUED)

- Automated CI tests for everything that we add to the SDK
  - Even trivial tests find bugs
  - It would be possible to run upstream Yocto Project's SDK tests in our SDK (some minor fixes are needed)
  - Users and CI jobs can extend the SDK with packages
- Qt Creator IDE with custom plugin to ease the development using the SDK
- Our SDK approach and tests have not yet been upstreamed
  - Planned for one of the next iterations
- The SDK contains tools and tests for the CI automated tests

SYSTEM BUILD – PACKAGE ARCHIVE

- Format: ipk
- Package archive with additional tools, debug symbols, development packages etc.
- Due to the complexity of corporate networks, we could not set up a single package repository server
- We distribute packages to a number of mirrors in different networks (even using different protocols)
- Some debugging tools are only available in the package repository
- We don't support incremental updates of SDK and images using the package repository yet
  - Due to the complexity of the network setup, we don't have a PR server
  - We bump PRs manually
  - We plan to reuse the PR server database files

SYSTEM BUILD - DIFFICULTIES WITH YOCTO PROJECT

- Writing proper BitBake recipes is a form of art - only a few people know how to do this correctly
  - BitBake is too flexible - too much freedom
- The shared sysroot approach in the context of parallel recipe processing causes build race conditions
  - Some software enable/disable features based on the state of sysroots
  - The state of sysroots vary as build tasks are executed
  - Undeclared build dependencies often go unnoticed
  - Developers add features to their software, but forget to specify dependencies in recipes
    - Sometimes packages build fine on populated sysroots, but break due to missing dependencies specification when built from scratch
  - Developers and CI build images, instead of changed recipes with an empty sysroot
  - Sstate cache hides problems until something triggers a rebuild
- Floating build dependencies
  - Features are implicitly enabled/disabled based on the state of sysroot
  - May cause build or test failures

SYSTEM BUILD - DIFFICULTIES WITH YOCTO PROJECT (CONT.)

- In our case, BitBake builds are not reproducible
- Packaging of language extensions (e.g., Java's maven, JavaScript's npm) is problematic
- Using specific package managers just hides the problem and lead to not reproducible builds
- Developers may call package managers like maven from their build scripts while generating code
  - Downloading modules from the Internet may fail
  - No guarantees with regard to integrity of downloaded modules
  - No sum checking and no caching on the BitBake side
  - May break packaging
  - No license tracking
- BitBake rebuilds dependents even when it is not strictly required
  - API/ABI compatibility is preserved
  - Leads to long build times

SYSTEM BUILD - NUMBERS

- For "`all`" (per target machine)
- More than 22K BitBake tasks
- More than 8K packages generated (~6.4GB)
- One SDK
  - ~600MB
  - ~1100 packages
- Nine images (numbers on the biggest):
  - ~510MB
  - ~845 packages

SYSTEM BUILD - PROFILE

- Build times may range from 20 minutes to 5 hours
- Build performance can be hard to optimize
  - Many variables to tweak
  - Different build characteristics, depending on what has to be compiled (BitBake caches)
  - Some heavy-weight components
    - Big C++ components
    - Some of the big ones are affected by dependencies that change frequently, so they have to be rebuilt
    - Several build steps cannot effectively utilize multiple CPUs
      - Some tasks like do_rootfs (image creation)
      - Run queue preparation
- buildstats data can be useful to understand builds

SYSTEM BUILD - POSTPROCESSING

- Check the presence of expected files
- Sstate cache preparation after releases
- Publishing of artifacts (packages, images, SDK, logs etc.)
- After a release, a new SDK is deployed into the system

BUILD OPTIMIZATIONS

DETERMINE BOTTLENECKS

- System resources
  - CPU
  - Memory
  - Disk I/O
  - Network I/O
- Require system monitoring tools
  - Performance co-pilot (pcp)
  - htop
  - buildstats
  - syslog
  - Grafana

DOWNLOAD CACHE

- Alleviates the load on some slower paths in the company's network
- A special BitBake job (-c fetchall) populates the cache into a NFS share which are mounted by the build slaves
  - Does not fully validate the downloads after `bitbake -c fetchall`
  - Corrupted downloads lead to build failures
- Ideally, we would like to be able to run offline builds (no network)

BITBAKE PARALLELIZATION SETTINGS

- BB_NUMBER__THREADS, PARALLEL_MAKE
- The default parallelization options set by BitBake don't work for build profile
  - Compilation of a single C++ file can consume gigabytes of physical RAM
  - Example: machine with 16 CPU cores (`PARALLEL_MAKE`=16, `BB_NUMBER_THREADS`=16)
    - Worst case: 256 compilation tasks running at the same time
    - We observed system load above 100
    - Some builds run out of RAM, which leads to heavy swapping or OOM killer (breaks builds)
  - Lesson learned
    - Measure and set resource limits for BitBake tasks (cgroups)
    - Ideally, the BitBake scheduler should take into account the system load when scheduling
    - Should not spawn tasks when load and memory usage reach some limit

OPTIMAL PARALLELIZATION IS HARD TO GET

- In cases of lots of caching, high parallelization is desired
- In cases of low caching, high parallelization may lead to system trashing due to high resource usage
- We use a custom script to set up parallelization options which takes number of CPU cores and RAM into account to set the parallelization options

BITBAKE PARALLELIZATION HEURISTIC

```
mem = get_mem_total()
cpus = get_number_cpus()
mem_cpus = (mem * 1.0) / cpus

if ncpus == 1:
    BB_NUMBER_THREADS, PARALLEL_MAKE = (1, 1)
elif mem_cpus > 8:
    BB_NUMBER_THREADS, PARALLEL_MAKE = (cpus, make_j(cpus))
elif mem_cpus >= 4:
    BB_NUMBER_THREADS, PARALLEL_MAKE = (cpus, make_j(divide_cpus(cpus, 2)))
elif mem_cpus >= 2:
    BB_NUMBER_THREADS = divide_cpus(cpus, 2)
    PARALLEL_MAKE = make_j(divide_cpus(cpus, 2))
else:
    BB_NUMBER_THREADS = divide_cpus(cpus, 2)
    PARALLEL_MAKE = make_j(divide_cpus(cpus, 4))
```

BUILD SLAVE TUNING

- Avoid "disk" I/O
  - Keep data on memory for as log as possible (Linux memory manager settings - sysctl)
    - `vm.dirty_background_bytes = 0`
    - `vm.dirty_background_ratio = 90`
    - `vm.dirty_expire_centisecs = 4320000`
    - `vm.dirtytime_expire_seconds = 432000`
    - `vm.dirty_bytes = 0`
    - `vm.dirty_ratio = 60`
    - `vm.dirty_writeback_centisecs = 0`
  - Avoid swapping
  - Lots of RAM help (up to certain point)
  - Increasing RAM from 64GB to 128GB on a machine with 40 CPU cores didn't improve build times
- More aggressive parallelization options lead to system trashing, thus slower builds
- Solution: experiment; profile the build and tune resources and parallelization options

QUALITY ASSURANCE AND SECURITY

STATIC CODE ANALYSIS USING CODE SONAR

– Finds CERT programming errors like memory leaks, buffer overflows and race conditions
– Similar to Coverity
– All the BitBake recipes are recompiled using Code Sonar's compiler wrapper
– Slow: takes roughly five days
– Automated, but not directly connected to the CI workflow

OPEN SOURCE LICENSE COMPLIANCE

– We use the license information provide by BitBake recipes
– Additionally, we use Black Duck's Protex to analyse source code for cases of license violation
– Automated, but not directly connected to the CI workflow

SECURITY VULNERABILITY ANALYSIS

- We need to know which CVEs affect our products
  - Tooling provided by Yocto Project patches
  - Black Duck also supports this, but we are not using it yet

CONCLUSIONS

ON YOCTO PROJECT

- Community support on mailing lists, IRC and bug tracker is good
- Documentation is good, but the system is complex
- Yocto Project's core meta layers are our reference in terms of quality
- It's difficult to achieve the same level of quality as Yocto Project's in our meta layers
- Some fundamental BitBake design decisions cause us some problems
  - Shared sysroots lead to build race conditions and dependency issues
  - Huge amount of global, mutable variables
  - No reproducible builds (in our case), even with the use of standard build environment (container)
    - We are working on making them reproducible and intend to have this feature by the time we ship the product

LESSONS LEARNED ON THE DESIGN OF OUR CI SYSTEM

– CI systems can be used to automate any task of the development process
– CI software builds find bugs
– CI tests, even if trivial, also find bugs
– Cultural change: some developers and project partners appreciate the feedback of the CI system
– Cultural resistance: some project partners and developers don't
– Quality of service in corporate network makes the implementation of CI systems difficult, reliability suffers
– Reliability of the system depends on the reliability of the parts (hypothetical example):
  – Source code servers: 95% availability
  – Build reliability: 90% and then developers changes on top
  – Tests: 90% reliability

=> 0.95 * 0.90 * 0.90 = 76,9% overall reliability

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