Reproducible Builds in FreeBSD

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BSDCan 2016 (Ottawa, Canada)
2016-06-11

About Me

- FreeBSD user since early 2000s
- FreeBSD committer since 2005
- FreeBSD Foundation since 2011
- Reproducible builds since 2015

About You

About You

- BSD src contributor or committer?

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- BSD ports maintainer or committer?

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- Have heard about reproducible builds?

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- BSD ports maintainer or committer?
- Contributed to Free / Open Source Software?
- Have heard about reproducible builds?
- Have worked on making software reproducible?

Reproducible Builds

Build software twice

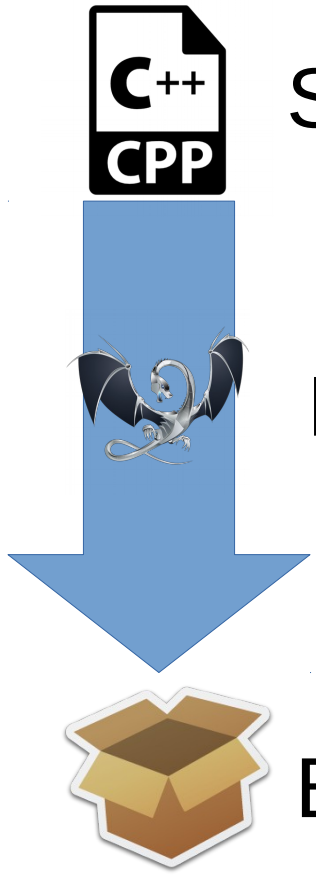
Reproducible Builds

Build software twice
and get the same result

Reproducible Builds

Build binary artifacts twice
and get the same result

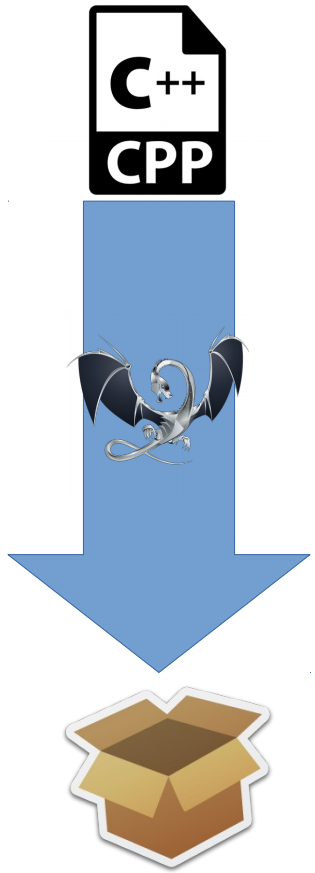
Source code

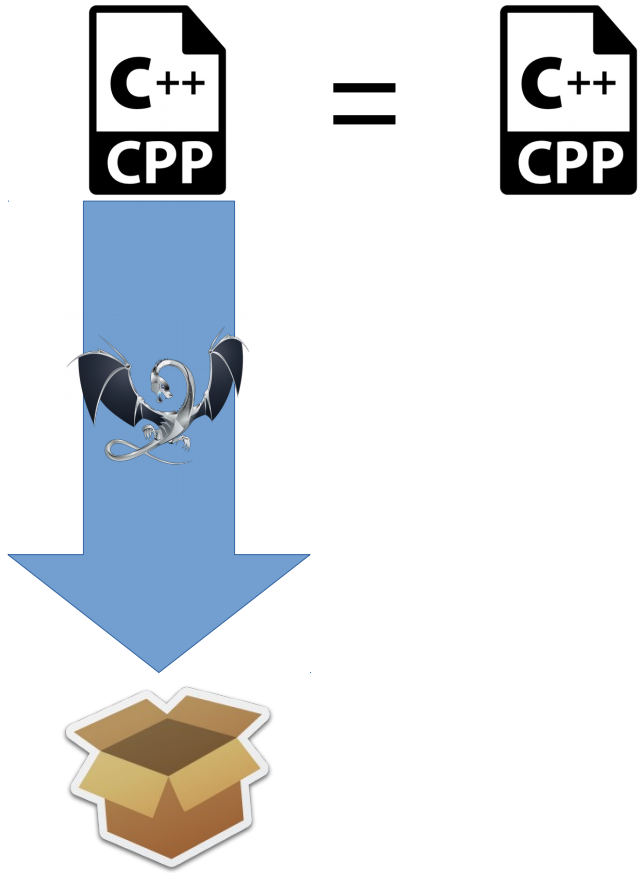


Source code

Build process

Binary artifact


C++
CPP


C++
CPP
=
C++
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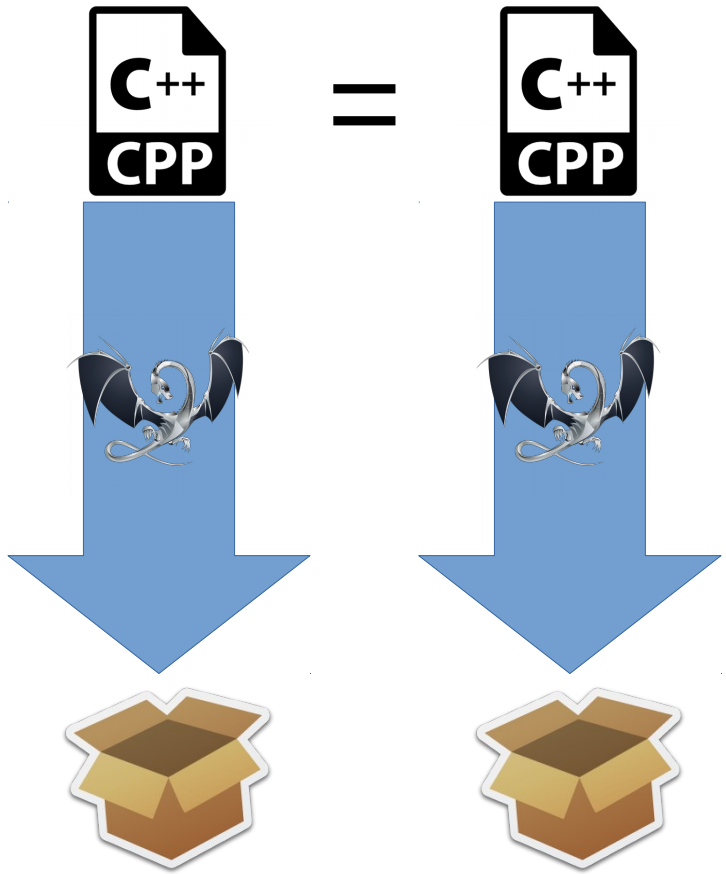
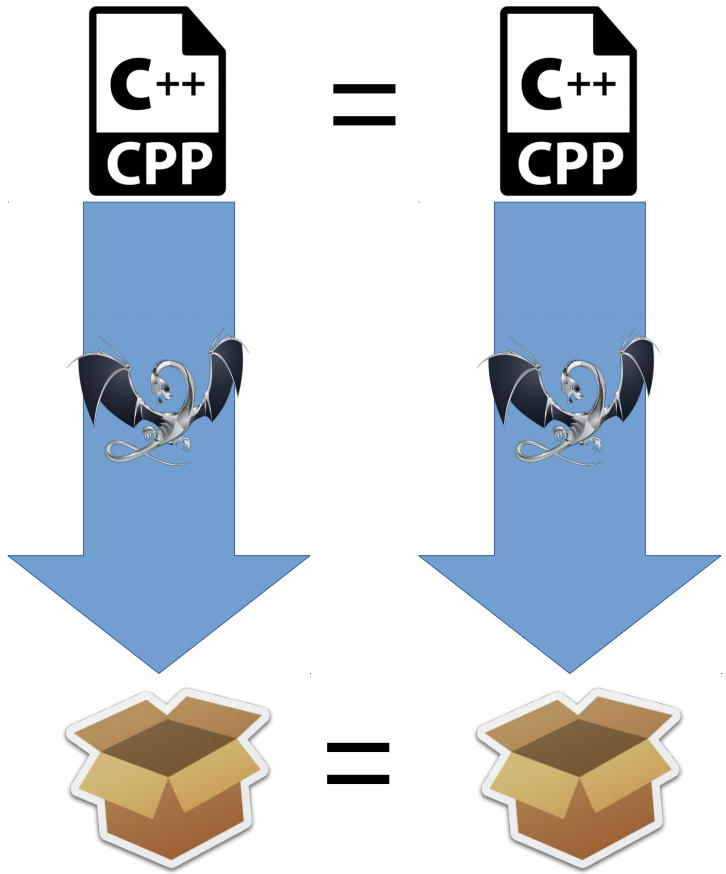

C++
CPP
=
C++
CPP


C++
CPP
=
C++
CPP
=

Why?

- Software Integrity / Assurance
- Practical Reasons

Practical Reasons

- Reduce package repository storage size (keeping all builds)
- Reduce bandwidth when mirroring, updating
- Create smallest binary patches
- Allow retroactive debug data creation

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- Accurate exp-runs

Practical Reasons

- Reduce package repository storage size (keeping all builds)
- Reduce bandwidth when mirroring, updating
- Create smallest binary patches
- Allow retroactive debug data creation
- Accurate exp-runs – track:
  - Changing toolchain components
  - Packages impacted by a change in a headers or macros
  - Packages using static libraries
  - Improved packaging Q/A

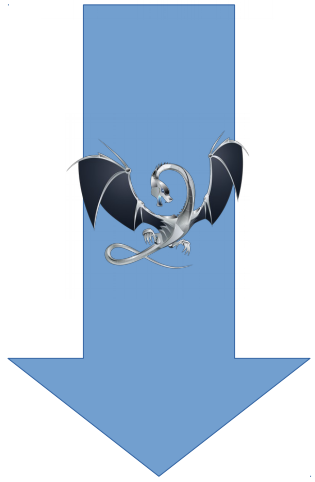
Software Assurance

"**Reproducible builds** are a set of software development practices which **create a verifiable path from** human readable **source code to** the **binary code** used by computers."

https://reproducible-builds.org/

Software Assurance

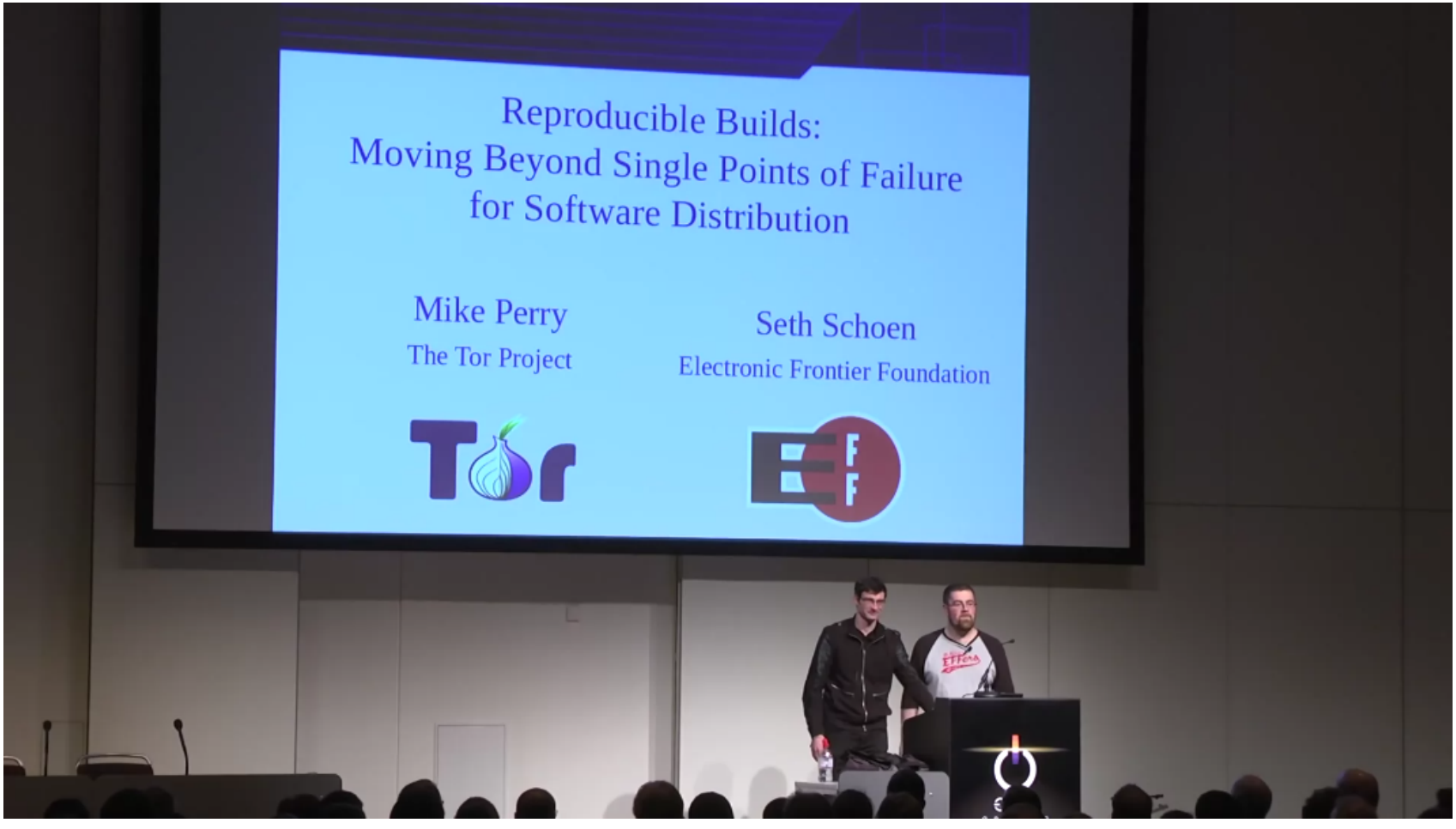
Can be verified



Can be used

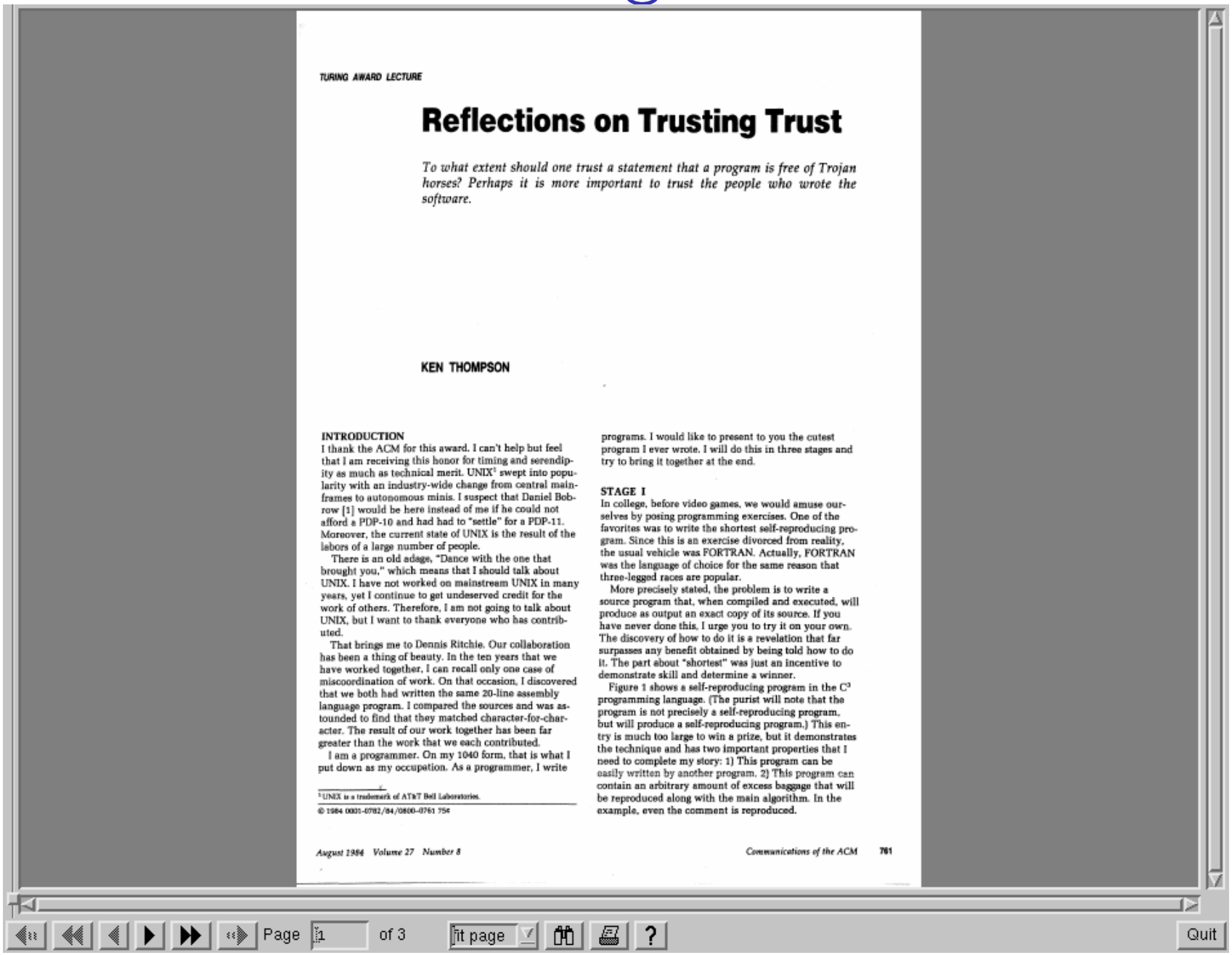
XCode Malware

31c3 Perry and Schoen



https://media.cc.de "Moving Beyond Single Points of Failure"

Reflections on Trusting Trust



TURING AWARD LECTURE

Reflections on Trusting Trust

To what extent should one trust a statement that a program is free of Trojan horses? Perhaps it is more important to trust the people who wrote the software.

KEN THOMPSON

INTRODUCTION

I thank the ACM for this award. I can't help but feel that I am receiving this honor for timing and serendipity as much as technical merit. UNIX[1] swept into popularity with an industry-wide change from central mainframes to autonomous minis. I suspect that Daniel Bobrow [1] would be here instead of me if he could not afford a PDP-10 and had had to "settle" for a PDP-11. Moreover, the current state of UNIX is the result of the labors of a large number of people.

There is an old adage, "Dance with the one that brought you," which means that I should talk about UNIX. I have not worked on mainstream UNIX in many years, yet I continue to get undeserved credit for the work of others. Therefore, I am not going to talk about UNIX, but I want to thank everyone who has contributed.

That brings me to Dennis Ritchie. Our collaboration has been a thing of beauty. In the ten years that we have worked together, I can recall only one case of miscoordination of work. On that occasion, I discovered that we both had written the same 20-line assembly language program. I compared the sources and was astounded to find that they matched character-for-character. The result of our work together has been far greater than the work that we each contributed.

I am a programmer. On my 1040 form, that is what I put down as my occupation. As a programmer, I write programs. I would like to present to you the cutest program I ever wrote. I will do this in three stages and try to bring it together at the end.

[1] UNIX is a trademark of AT&T Bell Laboratories.

STAGE I

In college, before video games, we would amuse ourselves by posing programming exercises. One of the favorites was to write the shortest self-reproducing program. Since this is an exercise divorced from reality, the usual vehicle was FORTRAN. Actually, FORTRAN was the language of choice for the same reason that three-legged races are popular.

More precisely stated, the problem is to write a source program that, when compiled and executed, will produce as output an exact copy of its source. If you have never done this, I urge you to try it on your own. The discovery of how to do it is a revelation that far surpasses any benefit obtained by being told how to do it. The part about "shortest" was just an incentive to demonstrate skill and determine a winner.

Figure 1 shows a self-reproducing program in the C[2] programming language. (The purist will note that the program is not precisely a self-reproducing program, but will produce a self-reproducing program.) This entry is much too large to win a prize, but it demonstrates the technique and has two important properties that I need to complete my story: 1) This program can be easily written by another program. 2) This program can contain an arbitrary amount of excess baggage that will be reproduced along with the main algorithm. In the example, even the comment is reproduced.

Who's Involved

Who's Involved

Who's Involved

- F-Droid
- Bitcoin
- Tor
- Signal
- OpenSUSE
- Ubuntu
- Guix
- NixOS
- ElectroBSD
- Qubes
- TAILS
- Subgraph

Components of Reproducible Builds

- Deterministic build system
- Reproducible build environment
- Distributing the build environment
- Rebuilding and checking the results

Deterministic build system

- Stable inputs
- Stable outputs
- Capture as little as possible from the environment

Sources of nonreproducibility

- Embedded build information
- Input file ordering (filesystem, locale)
- Archive metadata
- Unstable output ordering (e.g. hashes)
- Intentional randomness
- DWARF debug info paths
- Threaded producers
- Optimizations
- Value initialization
- Embedded signatures

Variations

- hostname, domainname
- Environment: `TZ`, `LANG`, `LC_ALL`, `USER`
- Timestamp, Y/M/D H:M:S

Variations

- hostname, domainname
- Environment: `TZ`, `LANG`, `LC_ALL`, `USER`
- Timestamp, Y/M/D H:M:S
- Year or date
- uid, gid
- Kernel version
- 32- or 64-bit kernel
- shell
- umask
- CPU type
- filesystem

Reproducible FreeBSD

- Base
- Ports

Reproducible FreeBSD

- Base
- Ports
- *Doc*

FreeBSD base

- Under our control
- Almost done
  - ReproducibleBuilds wiki page created in 2013
  - Prompted by FreeBSD-update

FreeBSD base - fixed

- Build date in `/usr/include/osreldate.h`
- Build host and user in `/usr/sbin/amd`
- Build date and time in `/usr/sbin/bhyve`
- Build date and time in `/etc/mail/*.cf`
- Build date in `/usr/share/doc/psd/13.rcs/paper.ascii.gz`

FreeBSD base - TODO

Build host, user, path and time in `/var/db/mergemaster.mtree`

```
#           user: emaste
#        machine: example
#           tree: /var/tmp/temproot.fFki3iM9
#           date: Sun Apr 10 12:19:52 2016

# .
/set type=file
.                 type=dir
    aliases       type=link
    amd.map       size=208 md5digest=e24ec9e1b9da870742a17669e69309a6
    apmd.conf     size=1233 md5digest=ad61867e7088f15356ce7a123b909859
    auth.conf     size=230 md5digest=5ced0a5986b19b6e60dcf25ca6d860b0
    crontab       size=723 md5digest=26d10036869afb3fd0569d9c09d44c4c
    csh.cshrc     size=106 md5digest=0fb9d8e625dcdaa81f70ee308c8135d6
    ...
```

FreeBSD base - TODO

Build user, date and time in /boot/loader/loader and other loaders

```
BTX loader 1.00  BTX version is 1.02
Consoles: internal video/keyboard
BIOS drive C: is disk0
BIOS 638kB/1046464KB available memory

FreeBSD/i386 bootstrap loader, Revision 1.1
(root@logan.cse.buffalo.edu, Thu Jan  1 09:55:10 UTC 2009)
Loading /boot/defaults/loader.conf
```

FreeBSD base - TODO

Build user, date and time in /boot/kernel/kernel

```
% uname -v
FreeBSD 9.1-RELEASE #0 r243825: Tue Dec  4 09:23:10 UTC 2012
root at farrell.cse.buffalo.edu:/usr/obj/usr/src/sys/GENERIC
```

FreeBSD base - TODO

- Full paths in non-debug sections in kernel modules
- Other sporadic kernel module differences
- Date or other metadata in filesystem image produced by makefs in `/tests/sys/geom/class/uzip`
- makewhatis output depends on man page device and inode numbers

FreeBSD ports

- Ports do not enforce build environment (user, host name, path, ...)
- Variation good for identifying nonreproducibility
- We want to facilitate reproducibility
- Poudrière

FreeBSD packages

- PortsReproducibleBuilds wiki page created in March 2015 (swills@)
- Initial patch sets stage dir timestamps to that of the newest distfile
- Builds vary the hostname, time, and date
- 15164 of 23599 packages reproducible (64.25%)

FreeBSD packages

- Second iteration by bapt@
- Record timestamp in `make makesum` during port update
  - Ports r415078 by emaste@
- Use timestamp for pkg archive metadata
- Use timestamp as `SOURCE_DATE_EPOCH` in build environment

Use timestamp for pkg archive metadata

Non-reproducible	5162
Reproducible	20009
Failed	4

- Example non-reproducible packages:
  GraphicsMagick, R-* *(181)*, ansible, apache-openoffice, apache24, aspell, autoconf, automake, avrdude, bind910, busybox, clamav, cmake, couchdb, courier, crashmail, cyrus-imapd25, dbus, distcc, dpkg, elixir-* *(61)*, erlang-* *(63)*, exim, fpc-* *(90)*, ficl, firefox, gcc, git, go, hadoop2, inkscape, kBuild, kde-runtime, lastpass-cli, libav, libdjbdns, libgcrypt, libgpg-error, libidn, liblz4, libtool, libxul, llvm38, m4, mongodb, node, octave-* *(91)*, openjdk, openldap-server, openvpn, owncloudclient, p5-* *(747)*, php56, py27-* *(195)*, python27, python34, qemu, ruby, rubygem-* *(1175)*, samba44, squid, subversion, tcl86, tex-luatex, thunderbird, u-boot-* *(11)*, valgrind, virtualbox-ose, vlc, wine, yacc, yasm

Set SOURCE_DATE_EPOCH in build environment

Non-reproducible	3534
Reproducible	5062
Failed	4

- Example packages of 116 more now reproducible:
  calibre, cherivis-devel, cmake, easydiff, freetar, gforth, gnumail, gnustep-wrapper, kbreakout, net-snmp, mongodb32, terminal.app

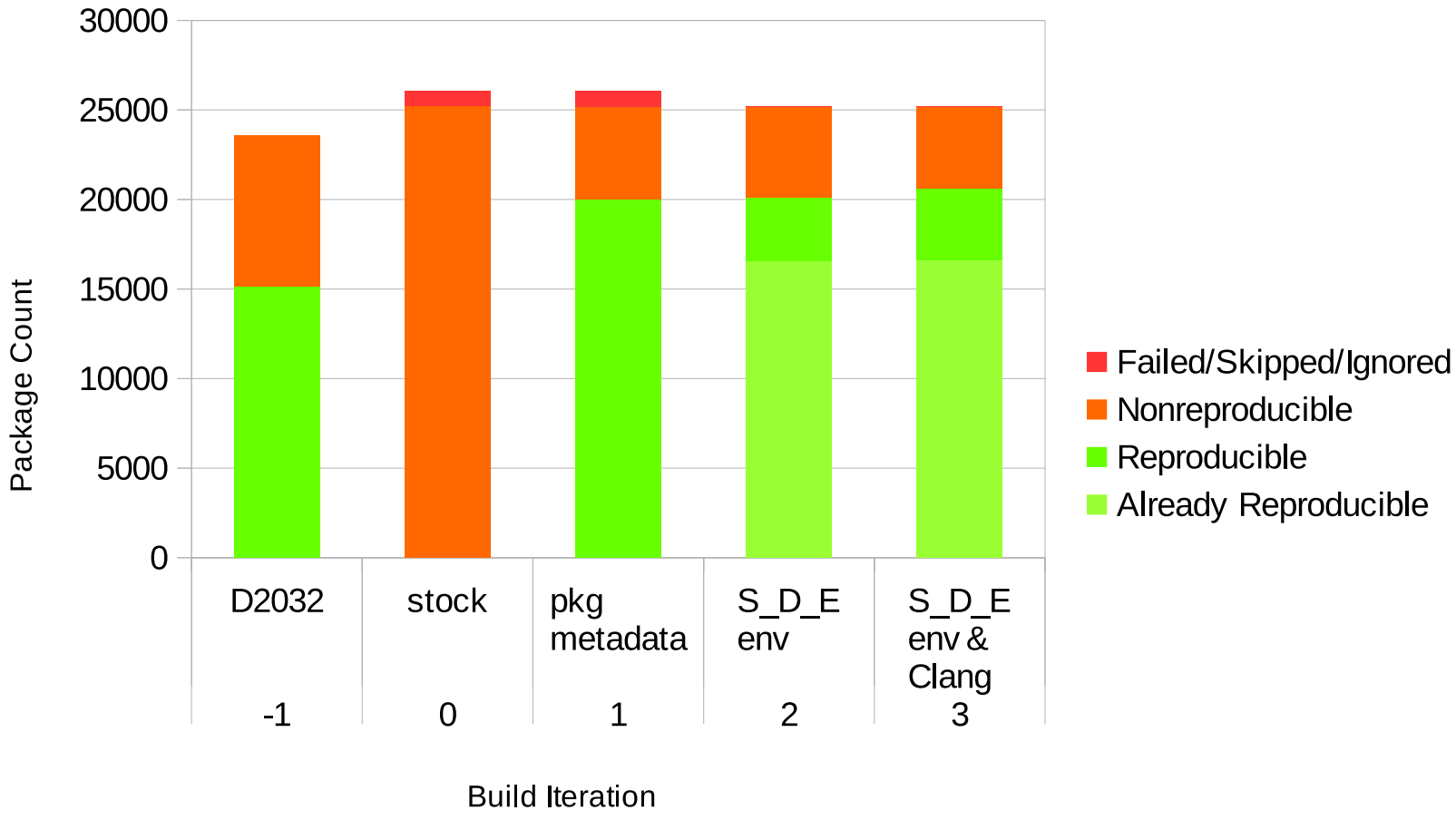
Set SOURCE_DATE_EPOCH in build environment + Clang patch

Non-reproducible	4011
Reproducible	4549
Failed	5

- Example packages of 514 more now reproducible:
  abiword, analog, apache22, audacity, avrdude, bind99, bind910, clamav, crashmail, ctags, distcc, efax, exim, inkscape, libcaca, liblz4, llvm-cheri128, nagios4, nasm, rrdtool, subversion, x264, xchat, unzip

			SOURCE_DATE_EPOCH		
	D2032	Stock	pkg	+build env	+Clang
Non-reproducible	15164	25222	5162	3534	4011
Reproducible	8435	0	20009	5062	4549
Failed		824	875	4	5
Reproducible %	64.26%	0%	79.49%	79.89%	81.92%

FreeBSD packages



Investigating Changes

What's changed?

- 1: `nginx-1.10.0_3,2.txz bb31ba88b568...`
- 1: `avrdude-6.1_1.txz 0a3811a78a03...`

What's changed?

- 1: `nginx-1.10.0_3,2.txz bb31ba88b568...`
- 2: `nginx-1.10.0_3,2.txz bb31ba88b568...`

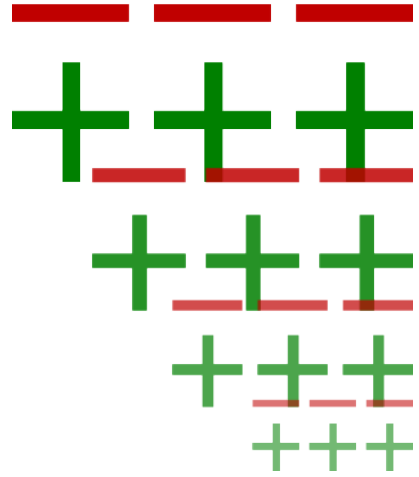
- 1: `avrdude-6.1_1.txz 0a3811a78a03...`

What's changed?

- 1: `nginx-1.10.0_3,2.txz bb31ba88b568...`
- 2: `nginx-1.10.0_3,2.txz bb31ba88b568...`

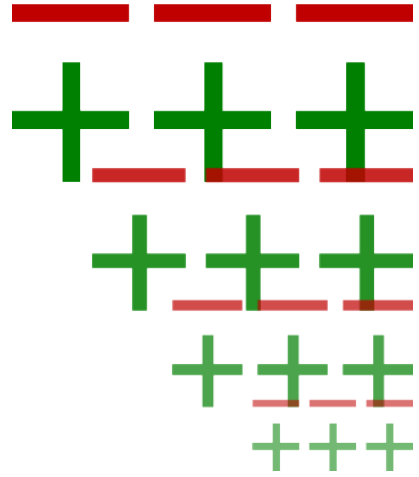
- 1: `avrdude-6.1_1.txz 0a3811a78a03...`
- 2: `avrdude-6.1_1.txz 7336a6d85dd6...`

Diffoscope



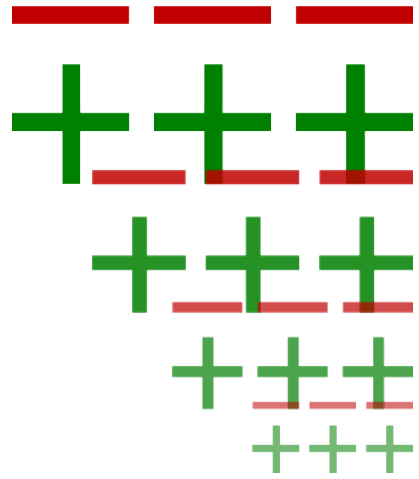
- Examine differences *in depth*
- Output HTML or plain text
- Recursively unpack archives
- Human readable output
  - Uncompress `.PDF`, disassemble binaries
- https://diffoscope.org
- FreeBSD port `sysutils/diffoscope`
- Online version https://try.diffoscope.org

Diffoscope



- Archives
  - bzip2, `.cpio`, `.deb`, gzip, `.ipk`, iso9660, RPM, squashfs, `.tar`, `.xz`, `.zip`
- Formats
  - Debian `.changes`, TrueType & OpenType fonts, gettext `.mo`, `.class`, Mono `.exe`, PDF, PNG, sqlite3 databases, text files

Diffoscope



- Archives
  - bzip2, `.cpio`, `.deb`, gzip, `.ipk`, iso9660, RPM, squashfs, `.tar`, `.xz`, `.zip`
- Formats
  - Debian `.changes`, TrueType & OpenType fonts, gettext `.mo`, `.class`, Mono `.exe`, PDF, PNG, sqlite3 databases, text files
- Maintainers wanted!

Nonreproducible binary

Example

```
% cat hello.c
#include <stdio.h>

int
main(int argc, char *argv[])
{
        puts("Hello, World compiled at "
             __TIME__ " on " __DATE__ "\n");
}
% cc -o hello_1 hello.c
% cc -o hello_2 hello.c
```

Diffoscope output

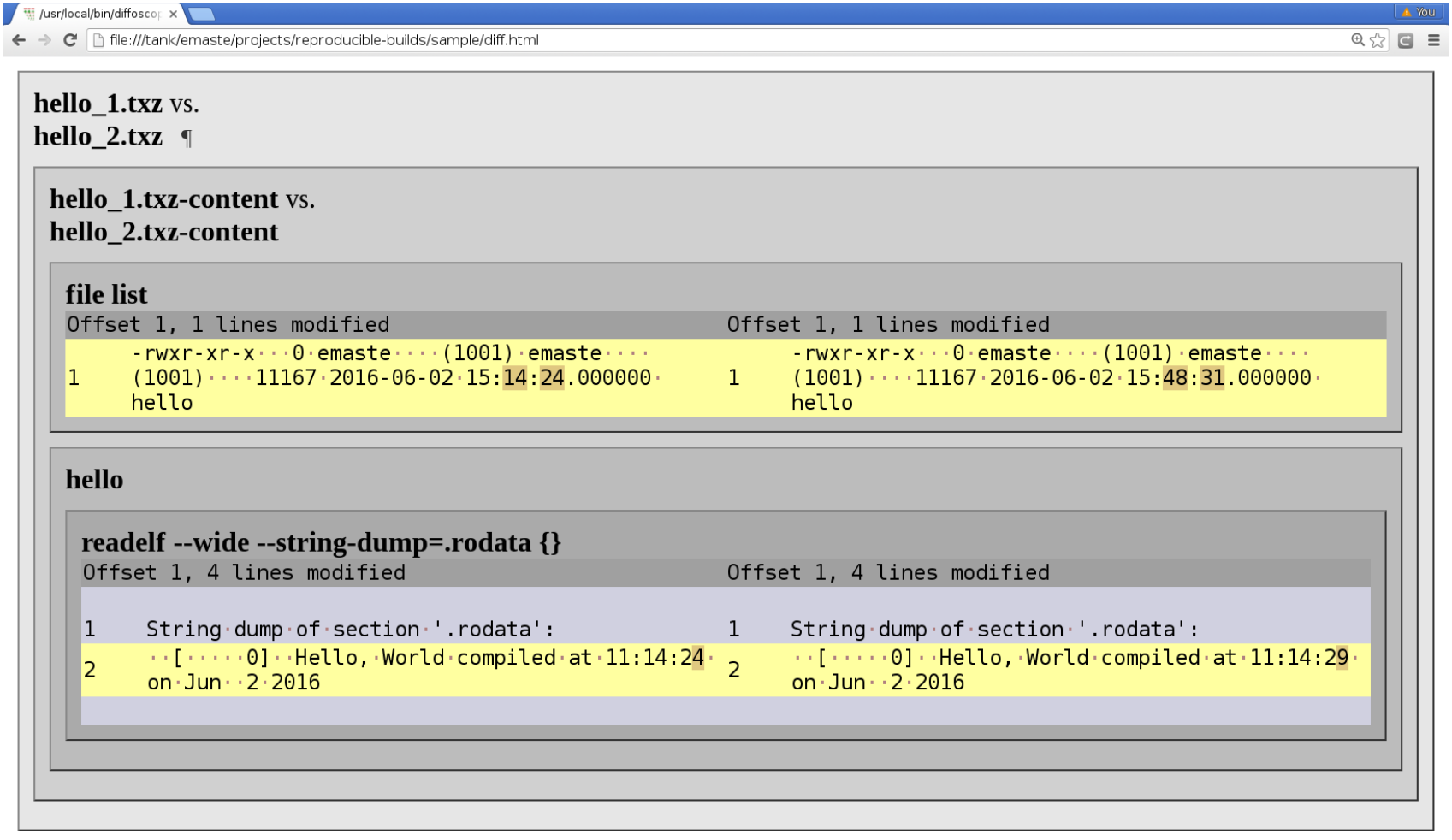
```
volta% diffoscope hello_1 hello_2
--- hello_1
+++ hello_2
├── readelf --wide --string-dump=.rodata {}
  @@ -1,4 +1,4 @@

   String dump of section '.rodata':
  -  [     0]  Hello, World compiled at 15:05:22 on Jun  6 2016
  +  [     0]  Hello, World compiled at 15:05:33 on Jun  6 2016


volta%
```

Diffoscope archives

Example

```
% cc -o hello hello.c
% tar -cJxf hello_1.txz hello
% cc -o hello hello.c
% tar -cJxf hello_2.txz hello
```

Diffoscope HTML output



Generated by diffoscope 49

Diffoscope

- Diffoscope is a **debugging** / **diagnostic** tool

Diffoscope

- Diffoscope is a **debugging** / **diagnostic** tool
- "Reproducible" means bit-for-bit identical
- `cmp` / `diff` / `sha256` test for reproducibility

Fixing nonreproducibility

Stable order for inputs

- Process inputs in the same order
- Directory order is not stable!

Example

```
tar -cf archive.tar src
```

Stable order for inputs

- Process inputs in the same order
- Directory order is not stable
- Solutions:
  - List inputs explicitly

Example

```
tar -cf archive.tar \
  src/util.c src/helper.c src/main.c
```

Stable order for inputs

- Process inputs in the same order
- Directory order is not stable
- Solutions:
  - List inputs explicitly
  - Sort explicitly

Example

```
find src -print0 | sort -z |
  tar -null -T - -no-recursion -cf archive.tar
```

Stable order for inputs

- Process inputs in the same order
- Directory order is not stable
- Solutions:
  - List inputs explicitly
  - Sort explicitly with explicit locale

Example

```
find src -print0 | LC_ALL=C sort -z |
  tar -null -T - -no-recursion -cf archive.tar
```

Deterministic version information

- Don't generate a version number on each build
- Extract information from the source:
  - Version control system revision
  - Hash of the source code
  - Changelog entry

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  - Hash of the source code
  - Changelog entry

Example (newvers.sh)

```
svn=‘cd ${SYSDIR} && $svnversion 2>/dev/null‘
...
#define VERSTR "...${svn}${git}${hg}..."
```

Eliminate build information

- `"Compiled by emaste on 2 May 2016 at 14:12:03"`

Eliminate build information

- ~~`"Compiled by emaste on 2 May 2016 at 14:12:03"`~~
- Just don't record build metadata:
  - Date and time
  - User name
  - Path
  - Hostname

Eliminate build information

- ~~`"Compiled by emaste on 2 May 2016 at 14:12:03"`~~
- Just don't record build metadata:
  - Date and time
  - User name
  - Path
  - Hostname
- **If the build is reproducible this information does not matter**

Don't record the current date and time

- Avoid timestamps

Don't record the current date and time

- Avoid timestamps
- But if one is needed,
  - Record a suitable timestamp in the build
  - Use date of last commit in VCS
  - Extract from changelog
  - Implement `SOURCE_DATE_EPOCH`

SOURCE_DATE_EPOCH

- Environment variable with a reference time to use instead of "current" time
- Number of seconds since UNIX Epoch (1970-01-01 00:00:00 UTC)
- Specification available
- Implemented in help2man, Epydoc, Doxygen, text2man, Ghostscript, groff, texlive, GCC, maven, ant, u-boot, vgabios, ...
- Clang patch in progress

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time

Example

```
tar -cf pkg.tar build
```

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value

Example

```
tar -mtime='2015-08-13 00:00Z' -cf pkg.tar build
```

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value

Example

```
tar -mtime='2015-08-13 00:00Z' -cf pkg.tar build
```

bsdtar does not support -mtime

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value
  - Pre-process file modification time

Example

```
touch -date="2015-08-13 00:00Z" build/* (GNU)
tar -cf pkg.tar build
```

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value
  - Pre-process file modification time

Example

```
touch -d "2016-06-11 00:00:00Z" build/*
tar -cf pkg.tar build
```

Don't record the current time (cont'd)

- Archive metadata inclues modification times
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value
  - Pre-process file modification time
  - Post-process archive

Example

```
# zip has no equivalent of -mtime
zip pkg.zip build
strip-nondeterminism pkg.zip
```

Explicitly set environment variables

- Some environment variables affect build output:
  - `LC_CTIME` (time strings)
  - `LC_CTYPE` (text encoding)
  - `TZ` (timezone)

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Explicitly set environment variables

- Some environment variables affect build output:
  - `LC_CTIME` (time strings)
  - `LC_CTYPE` (text encoding)
  - `TZ` (timezone)
- Set them to a controlled value
- Please don't override `LANG` (upstream)

Stable order for outputs

- Output lists in consistent order
- Typical issue: key order with hash tables

  perldoc.perl.org/perlsec.html#Algorithmic-Complexity-Attacks

Example

```
for module in dependencies.keys():
    version = dependencies[module]
    print('%s (>= %s)' % (module, version))
```

Stable order for outputs

- Output lists in consistent order
- Typical issue: key order with hash tables

  perldoc.perl.org/perlsec.html#Algorithmic-Complexity-Attacks
- Explicitly sort

Example

```
for module in sorted(dependencies.keys()):
    version = dependencies[module]
    print('%s (>= %s)' % (module, version))
```

Avoid true randomness

Sources of randomness:

- Temporary file names
- Generated UUIDs
- Filesystem images
- Protection against complexity attacks
- LTO (symbol names)
- Unique stamps in coverage data files

Avoid true randomness

- Compilers use a PRNG

Example

```
$ gcc -flto -c utils.c
$ nm -a utils.o | grep inline
0000000000000000 n .gnu.lto_.inline.381a277a0b6d
```

Avoid true randomness

- Compilers use a PRNG
- Seed with a known value
  - Use a fixed value

Example

```
$ gcc -flto -c -frandom-seed=0 utils.c
$ nm -a utils.o | grep inline
0000000000000000 n .gnu.lto_.inline.0
```

Avoid true randomness

- Compilers use a PRNG
- Seed with a known value
  - Use a fixed value
  - Extract from source code (filename, content hash)

Example

```
$ gcc -flto -c -frandom-seed=utils.o utils.c
$ nm -a utils.o | grep inline
0000000000000000 n .gnu.lto_.inline.a108e942
```

Avoid true randomness

- Compilers use a PRNG
- Seed with a known value
  - Use a fixed value
  - Extract from source code (filename, content hash)
  - Have make provide it

Example

```
$ gcc -flto -c -frandom-seed=${VAR:hash} utils.c
$ nm -a utils.o | grep inline
0000000000000000 n .gnu.lto_.inline.17b6a3ee
```

Volatile inputs can change or disappear

- npm left-pad

  `npm` ERR! 404 Registry returned 404 for GET on

  https://registry.npmjs.org/left-pad

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- Don't rely on the network (at all)

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- npm left-pad

  `npm` ERR! 404 Registry returned 404 for GET on

  https://registry.npmjs.org/left-pad
- Don't rely on the network (at all)
- But if you must,
  - Verify content using a cryptographic checksum
  - Have a backup under your control
- Like FreeBSD ports since r5390 (1995)

Controlled value initialization

- Don't record memory by accident

Example

```
static int write_binary(FILE *out, FILE *in, struct bimg_header *hdr)
{
        static uint8_t file_buf[MAX_RECORD_BYTES];
        struct bimg_data_header data_hdr;
        size_t n_written;

        data_hdr.dest_addr = hdr->entry_addr;
```

Controlled value initialization

- Don't record memory by accident
- Always initialize to a known value

Example

```
static int write_binary(FILE *out, FILE *in, struct bimg_header *hdr)
{
        static uint8_t file_buf[MAX_RECORD_BYTES];
        struct bimg_data_header data_hdr = { 0 };
        size_t n_written;

        data_hdr.dest_addr = hdr->entry_addr;
```

Reproducing the build environment

- Build tools and versions
- Build architecture
- Operating system
- Build path
- Build date and time
- ...

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Distributing the build environment

- Fetch and build known toolchain
- Integrated toolchain source
- Packaged toolchain
- Gitian
- Containers
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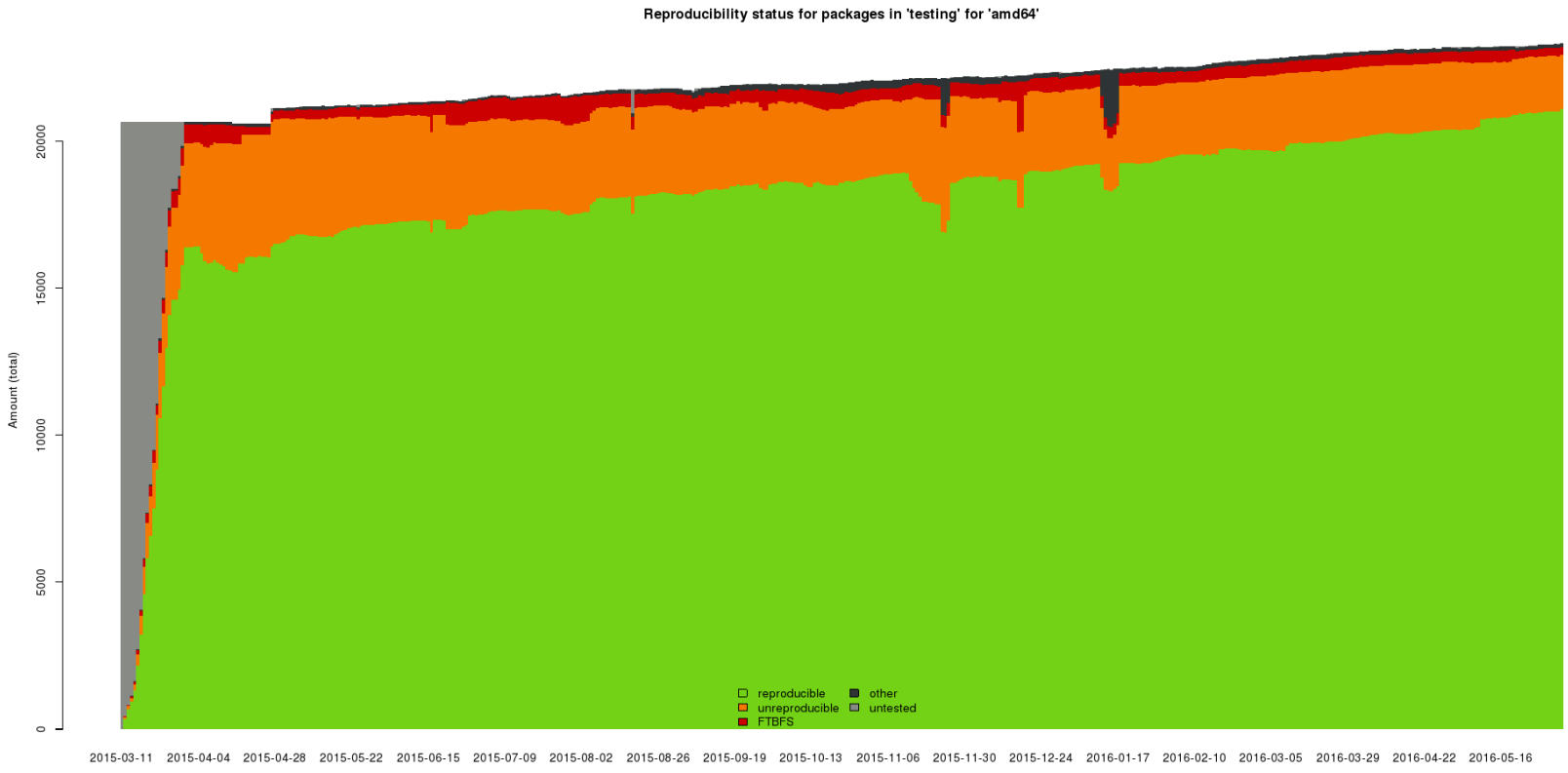
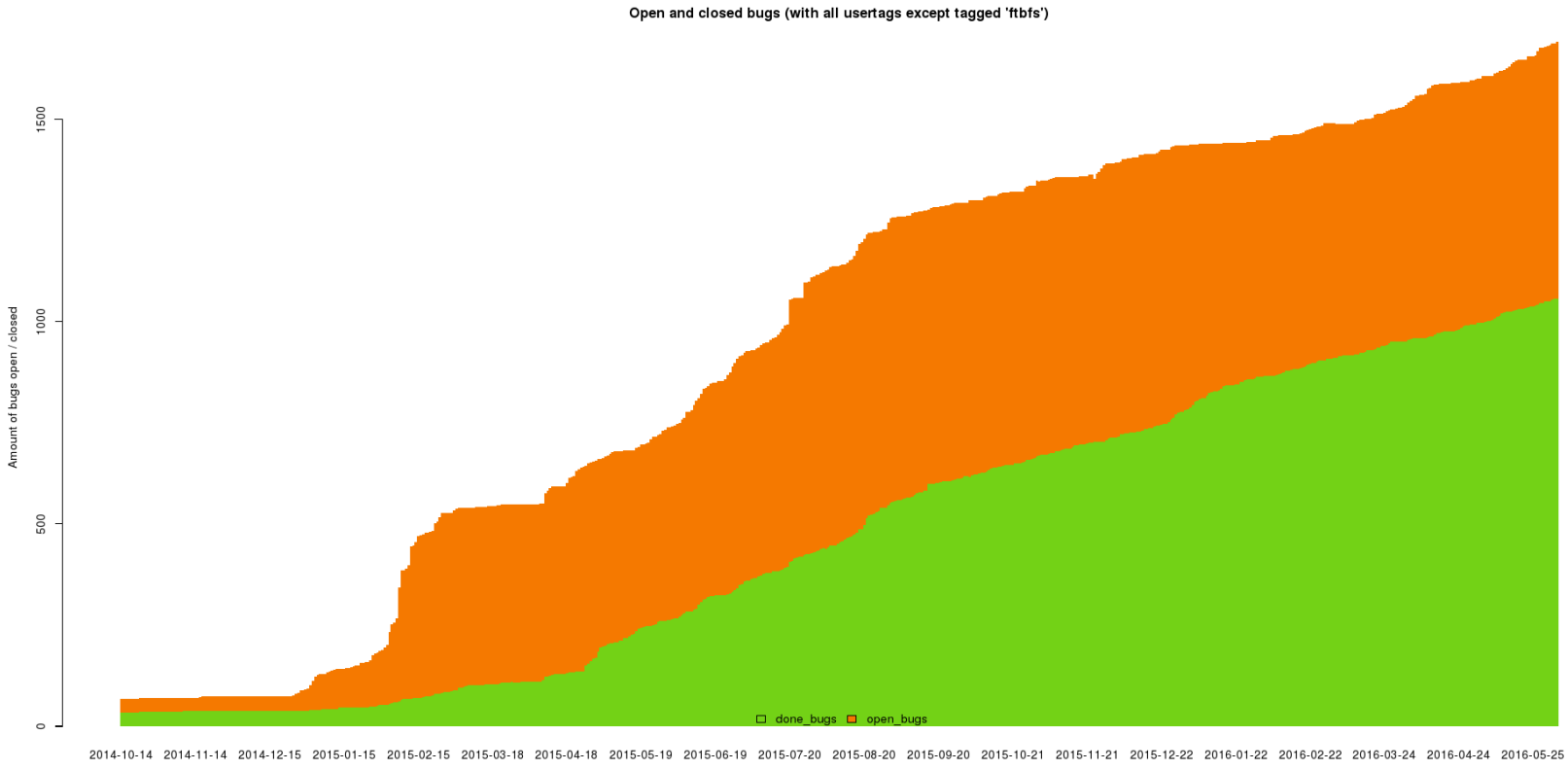
Debian's Experience - CI



Debian's Experience - Bugs



Debian's Experience - Buy-in

- Provide good arguments on why reproducible builds matter
  - ROI on security-related work not always apparent
- Continuous integration to track progress
- Reproducibility bugs come with patches

Debian's Experience - Policy

- Debian Policy Manual
  - Structure and contents of the Debian archive
  - Design issues of the operating system
  - Technical requirements packages must satisfy to be included
- Section 4.15:
  "Source must build in a reproducible manner"

Debian's Experience - Policy

- Debian Policy Manual
  - Structure and contents of the Debian archive
  - Design issues of the operating system
  - Technical requirements packages must satisfy to be included
- Proposed section 4.15:
  "Source must build in a reproducible manner"

OK - Now what?

- Builders / Rebuilders
- Distribution of reproduction results
- User interface

Thank you

Links

- Reproducible Builds https://reproducible-builds.org/
- Diffoscope https://diffoscope.org/
- FreeBSD Reproducible Builds wiki
  https://wiki.freebsd.org/ReproducibleBuilds
- FreeBSD Reproducible Ports wiki
  https://wiki.freebsd.org/PortsReproducibleBuilds
- Debian Reproducible Builds wiki
  https://wiki.debian.org/ReproducibleBuilds
- Diverse Double-Compilation
  http://www.dwheeler.com/trusting-trust/