How to make your software build reproducibly

Provide a verifiable path from source to binary

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Hi! I'm Lunar. I'm very much alive and feel really honored to be here.

Couple of words about me: I believe that humans should be controlling machines and not the other way around. That's why I'm a strong supporter of free software. I'm officialy a Debian Developper since 2007, and involved in the Tor Project since 2009. I need to say the work I'm presenting is also the work of many different people involved in Debian and in other projects.

And it's my involvement in Tor that got me interested in the topic I am going to talk about today. So what is the issue that we faced there?

The problem

source —build→ binary

When we talk about software, there are two sides of it. Source is what some humans can read. Binary can also be read, but only by a really tiny fraction of humanity. Binary form is what the computers need to run the software. Transforming the source code into binary format is code "compiling" or "building".

The problem

free software
freedom to study
freedom to run
source —build→ binary

The great thing with free software is that we have the freedom to study that the source code is doing what it is supposed to be doing. That it does not contain any malware, malicious code, or security bugs. Free software also gives us the freedom to run the software in any way we want.

The problem

source —build→ binary
can be verified
can be used

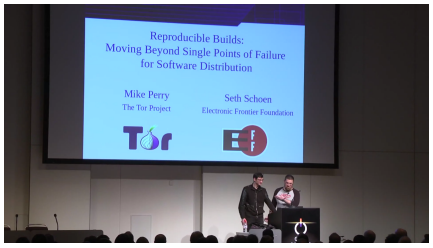
So, we have the source code that we can verify and we have a binary we can use. Question: when we download software in binary form, how do we know how it was built? Well, right now in almost every cases, your only choice is to trust the software author, or the distribution, that the archive with the source that has approximatively the same name is what has been used to create the binary.

The problem

source —build→ binary
can be verified
can be used
could I get a proof?

Wouldn't it be much better if we could get a proof?

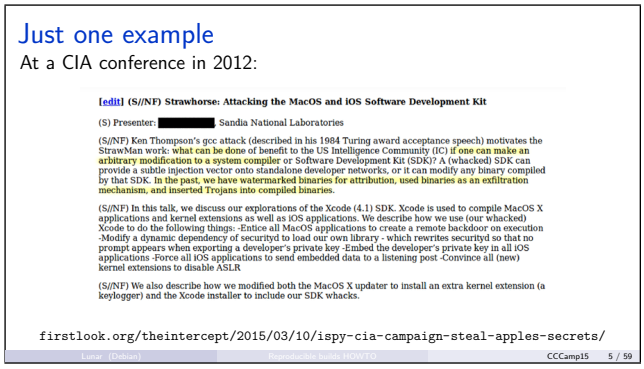
Why does it matter?



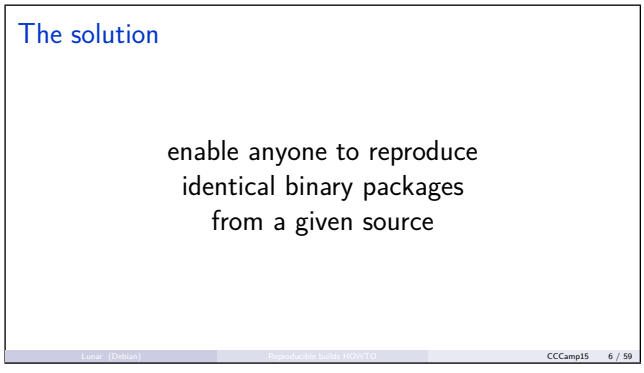
Available on media.ccc.de, 31c3

Some people could say that we need to trust the soft-

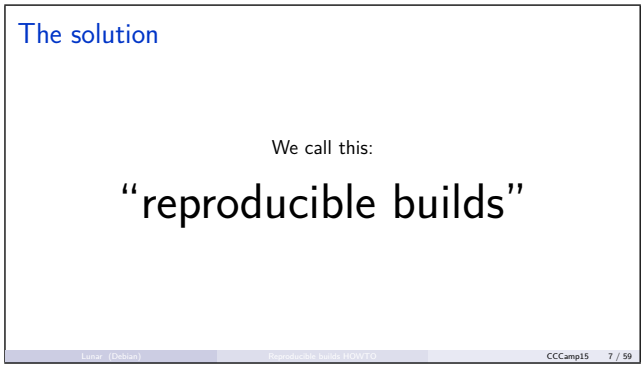
ware author, or the distribution, in all cases. Well, we indeed have to trust the software author and the distribution channel. But we have processes to do that, cryptographic signatures and all that jazz. But as Mike Perry and Seth Schoen explained in greater length during a talk last December at the 31C3, developers might be targeted and not realize that their building environment has actually been compromised. During the talk, Seth showed a proof-of-concept kernel exploit that would modify—without touching anything on the disk—a source file while it was being read by the compiler.



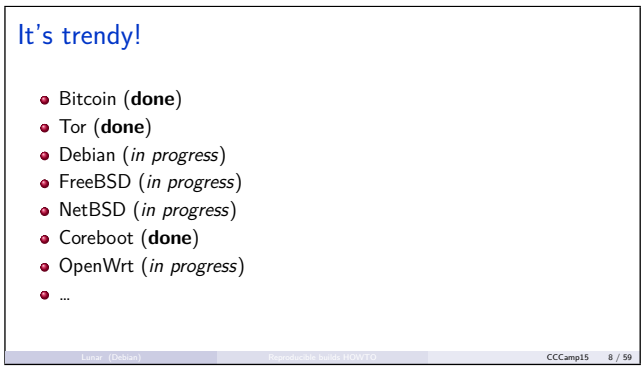
And we are not discussing hypothetical attacks here! A couple of months after Mike & Seth's talk, The Intercept released another document from the Snowden leaks describing the program of an internal CIA conference in 2012. The presentation that we see here was about "Strawhorse" and describes an attack on XCode—the software development environment for Mac OS X and iOS. They had a modified version, ready to be implanted on developer's systems, that would create binaries being watermarked, or leaking data, or containing trojans… And this is all without the developper realizing that this is happening. So even if we trust our developpers: they might totally be of good faith… and we would still totally get owned.



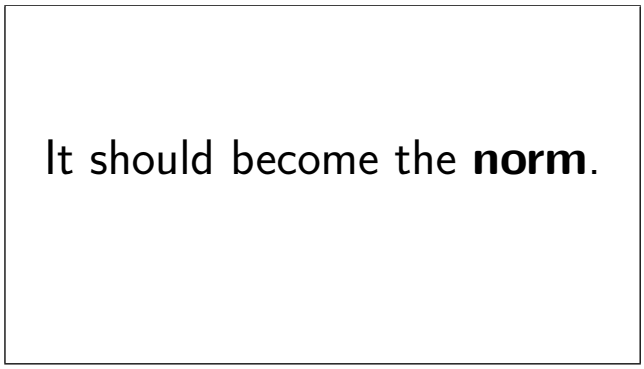
So what can we do about it? We need be able to get reasonable confidence that a given binary was indeed produced using its supposed source. To achieve this, we want to enable anyone to reproduce identical binary packages from a given source. If we have this, and then enough people to perform another build on different computers, on different networks, at different times, then we can assume that either everybody is compromised the same, or—with better luck—that no bad stuff got added behind our backs.



We call this idea: "reproducible builds".



Good news: it's getting trendy. I became familiar with the concept because of the work done by Mike Perry to get Tor Browser to build reproducibly. Himself, he was inspired by concerns in the Bitcoin community. It's been two years that we've started to work on this in Debian. Some people have started to work on FreeBSD. Coreboot fixed all the reproducibility problems in the past months. OpenWrt has started to accept some patches to make this possible. And it's not limited to these projects. We are seeing many people who are interested in making their project "reproducible" or making their tools able to produce identitical binaries.



And that's a very good thing because "reproducible builds" should become the norm. One say the only software that can be secure are free software because we can perform proper audit. But this really only apply when we can trust the binaries. As software developers, we do want to provide a verifiable path from the source to the binaries we distribute.

Multiple aspects

- Deterministic build system
  for those who write source code
- Reproducible build environment
  for those who create binaries for others
- Distributing the build environment
  for those who distribute binaries to the world
- Performing a rebuild and checking the results
  for every one of us

While working on this for the past two years in Debian, and kinda becoming a reference on the topic without us realizing it, we identified that there were multiple aspects to getting "reproducible builds". First you need to get the build to output the same bytes for a given version. But others also must to be able to set up a close enough build environment with similar enough software to perform the build. And for them to set it up, this environment needs to be specified somehow. Finally, you need to think about how rebuilds are performed and how the results are checked. I'm not going to talk about this last point in this presentation. It's mostly a matter of documentation because we advocate that checking the results should be as easy as comparing if the build products are byte for byte identical.

So first, how do we get a build system to always build the same thing.

Deterministic build system

In a nutshell:

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

In a nutshell, you need to make sure the inputs are always the same. That the outputs are always the same. And that as little as possible from the environment is being captured. Sounds like common sense?

Common problems

- Timestamps (recording current time)
- File order
- (Pseudo-)randomness:
  - Temporary file paths
  - UUID
  - Protection against complexity attacks
- CPU and memory related:
  - Code optimizations for current CPU class
  - Recording of memory addresses
- Build path
- Locale and timezone settings

Yet, with the work we've done in Debian, we've seen that these assumptions do not hold for a lot of the software we build. The number one issue preventing the output to always be the same is "timestamps". The date and time of the build creeps everywhere, we'll get back to this. Other common problems are variations in file ordering on disk, usage of randomness, specialized code for a given CPU class, the directory in which the build is being performed getting embedded in binaries, or other settings like locale or timezone affecting what gets recorded. But first, before giving some solutions to all these problems…

```
$ gem install hpricot --source http://code.whytheluckystiff.net
ERROR:  Could not find a valid gem 'hpricot' (>= 0) in any repository
ERROR:  While executing gem ... (Gem::RemoteFetcher::FetchError)
    SocketError: getaddrinfo: Name or service not known (http://code.whyth
eluckystiff.net/latest_specs.4.8.gz)
$
```

To build some piece of software, we actually need to get our hands on its source… WhyTheLuckyStiff was an amazing member of the Ruby community. If you meet someone who doesn't like Ruby, that's because they never had the chance to read _why's Poignant Guide to Ruby. Why am I talking about _why? Because one day, he disappeared and took all his websites, writings and code down…

Volatile inputs can disappear

- Don't rely on the network
- If you do:
  - Verify content using checksums
  - Have a backup
- The binary distributor should provide a fallback

FreeBSD does it right

```
$ grep MASTER_SITES Makefile
MASTER_SITES= http://gondor.apana.org.au/~herbert/dash/files/
$ cat distinfo
SHA256 (dash-0.5.8.tar.gz) = c6db3a237747b02d20382a761397563d813b306c020ae28ce25…
SIZE (dash-0.5.8.tar.gz) = 223028
$ wget http://distcache.freebsd.org/ports-distfiles/distfiles/dash-0.5.8.tar.gz
```


Inputs from the network—even if it doesn't seem like it—are volatile. So don't make your build system rely on remote data. Or if you do, use checksums to make sure the content has not been modified and keep backups. Ideally, provide a fallback location with these backups. A good example is how the FreeBSD ports work: they record `MASTER_SITES` for a given piece of software, the size and a cryptographic checksum for each files downloaded from

these master sites, but they also keep a copy of each files on their mirrors. That's the best way to handle network inputs, but if you can avoid them, do it. Ok, now let's tackle some of the common issues…

archive.tar

metadata

Offset 1, 4 lines modified		Offset 1, 4 lines modified	
1	-rwxr-xr-x lunar/lunar 0 2015-08-04 19:01:52 src/	1	-rwxr-xr-x lunar/lunar 0 2015-08-04 19:01:52 src/
2	-rw-r--r-- lunar/lunar 88191 2015-08-04 19:01:52 src/helper.c		
3	-rw-r--r-- lunar/lunar 12780 2015-08-04 19:01:37 src/util.c	2	-rw-r--r-- lunar/lunar 12780 2015-08-04 19:01:37 src/util.c
		3	-rw-r--r-- lunar/lunar 88191 2015-08-04 19:01:52 src/helper.c
4	-rw-r--r-- lunar/lunar 1173 2015-08-04 19:01:24 src/main.c	4	-rw-r--r-- lunar/lunar 1173 2015-08-04 19:01:24 src/main.c

Generated by diffoscope 28

Here we can see the differences between two Tar archives. They both contain exactly the same files. But, as you can see, not in the same order.

Stable order for inputs

- Always process multiple inputs in the same order
- Directory listings are not stable!

Example

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


This is an example of having a different output because the order of inputs is not stable. When doing the basic operation of listing a directory, there is no guarantees on the order in which they will be returned. So if you use `tar` as shown at the bottom, you don't know in which order files in the `src` directory will be written in the archive.

Stable order for inputs

- Always process multiple inputs in the same order
- Directory listings are not stable!
- Solutions:
  - List inputs explicitely

Example

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


One solution to this is to list all inputs explicitly. The construction here is actually pretty common for source code already.

Stable order for inputs

- Always process multiple inputs in the same order
- Directory listings are not stable!
- Solutions:
  - List inputs explicitely
  - Use sorting

Example

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


Another option is to use sorting. If you want to do it right for `tar` you actually need to use `find`, `sort` and `tar` in succession like shown. But there's a catch!

Stable order for inputs

- Always process multiple inputs in the same order
- Directory listings are not stable!
- Solutions:
  - List inputs explicitely
  - Use sorting
  - But watch out for difference between locales.

Example

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


Depending on the locale, the `sort` command will sort files differently. Typically, some locales will sort all uppercase letters together, while some other will be case-insensitive. So don't forget to specify the locale when using `sort`.

build/cbfs/fallback/bootblock.bin

Offset 1, 10 lines modified		Offset 1, 10 lines modified	
1	00000000: bada baab 0200 0000 5845 0000 0000 009a ....XE......	1	00000000: bada baab 0200 0000 5845 0000 0000 009a ....XE......
2	00000010: 1200 0000 9c5e 0000 4b1d 0000 4045 0000 .....^..K...@E..	2	00000010: 1200 0000 9c5e 0000 4b1d 0000 4045 0000 .....^..K...@E..
3	00000020: 0000 009a 17b9 e22a 009b 1d3c 0020 bd27 ....*...<. '	3	00000020: 0000 009a 1719 e252 009b 1d3c 0020 bd27 ....R...<. '
4	00000030: 009b 083c 0000 0825 fcff a923 adde 0a3c ...<...%...#...<	4	00000030: 009b 083c 0000 0825 fcff a923 adde 0a3c ...<...%...#...<
5	00000040: efbe 4a35 0000 0aad feff 0915 0400 0821 ..J5.........!	5	00000040: efbe 4a35 0000 0aad feff 0915 0400 0821 ..J5.........!
6	00000050: 2700 0010 0000 0000 feff 0010 0000 0000 '...............	6	00000050: 2700 0010 0000 0000 feff 0010 0000 0000 '...............
7	00000060: 1800 998c 0800 2003 1c00 848c e8ff bd27 ....'	7	00000060: 1800 998c 0800 2003 1c00 848c e8ff bd27 ....'
8	00000070: 5a00 822c 1000 b0af 2180 8000 0800 4014 Z..,....!.....@.	8	00000070: 5a00 822c 1000 b0af 2180 8000 0800 4014 Z..,....!.....@.
9	00000080: 1400 bfaf 009a 053c 009a 063c 2120 0000 ....<...<! ..	9	00000080: 1400 bfaf 009a 053c 009a 063c 2120 0000 ....<...<! ..
10	00000090: 4839 a524 7039 c624 e201 800e 4200 0724 H9.$p9.$....B..$	10	00000090: 4839 a524 7039 c624 e201 800e 4200 0724 H9.$p9.$....B..$

Here's another example taken from Coreboot and it's the kind of issue you really don't want to have to track down. Mike Perry and Georg Koppen faced such an issue with the Windows build of Tor Browser. The difference we're seeing here is only a couple of bytes. And these bytes will be different with almost all builds, and with no predictable or common patterns. That's because they are actually the content of whatever contains the memory at that time.

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;
        …
```


And using random values from memory will not produce deterministic output. So don't record memory by accident. Here we can see Coreboot code that was actually producing the dump we've just seen.

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;
        …
```


And as you can see the fix is trivial. So remember to always initialize all data structures you are using. Because tracking down the source of these kind of problems can really be a pain.

./usr/lib/aspell/de_affix.dat

Offset 1, 11 lines modified		Offset 1, 11 lines modified	
1	# this is the affix file of the de_DE Myspell dictionary	1	# this is the affix file of the de_DE Myspell dictionary
2	# derived from the igerman98 dictionary	2	# derived from the igerman98 dictionary
3	#	3	#
4	# Version: 20131206 (build 20150801)	4	# Version: 20131206 (build 20150802)
5	#	5	#
6	# Copyright (C) 1998-2011 Bjoern Jacke <bjoern@j3e.de>	6	# Copyright (C) 1998-2011 Bjoern Jacke <bjoern@j3e.de>
7	#	7	#
8	# License: GPLv2, GPLv3 or OASIS distribution license agreement	8	# License: GPLv2, GPLv3 or OASIS distribution license agreement
9	# There should be a copy of all of this licenses included	9	# There should be a copy of all of this licenses included
10	# with every distribution of this dictionary. Modified	10	# with every distribution of this dictionary. Modified
11	# versions using the GPL may only include the GPL	11	# versions using the GPL may only include the GPL

Another example. Here we see a build number embedded in a German dictionary for `aspell`, and that gets to be different from one build to another.

Use deterministic version information

- Don't generate a version number on each build

Don't do that. We want stable output, so it's a bad idea to create a new version or "build number" on each build.

Use deterministic version information

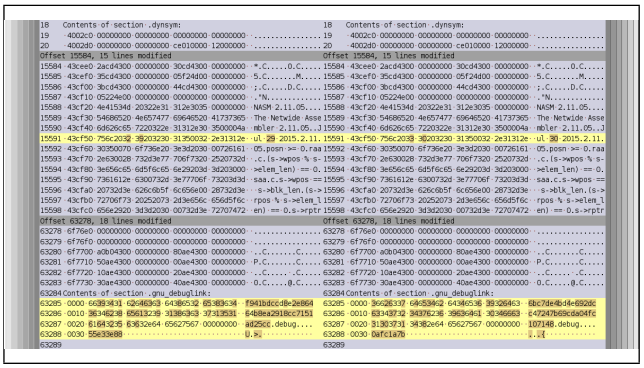
- Don't generate a version number on each build
- Instead extract information from the source:
  - Version control system revision
  - Hash of the source code
  - Changelog entry

Example

```
VERSION=$(shell dpkg-parsechangelog | sed -n 's/^Version: *//p')

SCONSOPTS = $(SCONSFLAGS) VERSION=$(VERSION) \
  PREFIX=$(PREFIX) PREFIX_CONF=$(SYSCONF) CHMDOCS=0 \
  STRIP_CP=no \
  $(if $(findstring nostripfull,$(DEB_BUILD_OPTIONS)),STRIP_W32=no,)
```


Instead, be deterministic and extract an information actually meaningful to the source that is being built. It can be the revision number from version control system. A hash of the source code might even be a better idea. Good thing about Git: they are the same. Another option is to extract stuff from a "changelog". The example here is an extract from how it's done for the `nsis` Debian package.



That's a dump of the `nasm` binary. The difference between these two builds is fairly obvious: on the left, we have July 29, and on the right, it's using the date of the next day, July 30.

Don't record the current date and time

- Avoid timestamps

It's one of the many many examples where the date and time of the build is being recorded by the build process, leading to different outputs. So, to sum it up: timestamps, bad idea. The current date and time is not really a useful piece of information anyway: you can always take an old piece of software and build it today. If the date and time of the build is meant to be an indication of the environment in which the build was made, then, as you'll see, more precise ways are needed anyway to get reproducible builds.

Don't record the current date and time

- Avoid timestamps
- If you need one:
  - Use date of last commit in VCS
  - Extract from changelog

So, if you really need to have a date and time recorded, then like for version numbers, make the date relevant to the source code. Get the date of the latest commit to the version control system. Or extract it from a changelog.

Don't record the current date and time

- Avoid timestamps
- If you need one:
  - Use date of last commit in VCS
  - Extract from changelog
  - Don't forget the timezone

But in that case, don't forget to record and use the original timezone or do everything in UTC. Otherwise, depending on where the build is made, you are likely to get different results.

Don't record the current date and time

- Avoid timestamps
- If you need one:
  - Use date of last commit in VCS
  - Extract from changelog
  - Don't forget the timezone
- `faketime` is an option but has serious drawbacks
  `https://bugs.torproject.org/12240`

One tool to avoid timestamp-related issue is `faketime`. `faketime` is a library that is loaded through the `LD_PRELOAD` environment variable and that will catch calls asking the system for the current time of day, and reply instead a predefined date and time. In some cases, it works just fine and can solve problems without requiring many changes to a given build system. The problem is that some tools rely on accurate times. The very common *Make* being one of them. *Make* requires accurate times because it will do it's best to only recompile stuff when the sources have changed since the last time a build happened. It gets really bad when doing parallel builds. The bug linked here is a reproducibility issue affecting the Tor Browser where `faketime` has the side effects that some objects are actually built multiple times because *Make* can't properly determine if they are too old or not, and in the end the ordering of some object files differ. So I would recommend to avoid `faketime` as much as possible, but handled with care, for limited uses, it can be an option. So, what should we do instead when some tool we use does record the current time?

Don't record the current date and time

- Avoid timestamps
- If you need one:
  - Use date of last commit in VCS
  - Extract from changelog
  - Don't forget the timezone
- `faketime` is an option but has serious drawbacks
  `https://bugs.torproject.org/12240`
- Implement `SOURCE_DATE_EPOCH`

A much better idea is to implement or support `SOURCE_DATE_EPOCH`.

SOURCE_DATE_EPOCH

- What is it?
  - Environment variable with a reference time
  - Number of seconds since the Epoch (1970-01-01 00:00:00 +0000 UTC)
  - If set, replace "current time of day"
  - Implemented by `help2man`, Epydoc, Doxygen, Ghostscript (in Debian)
  - Patches ready for GCC, `txt2man`, `libxslt`, Gettext...

`https://wiki.debian.org/ReproducibleBuilds/TimestampsProposal`

`SOURCE_DATE_EPOCH` is a new "standard" initially driven by Ximin Luo and Daniel Kahn Gillmor we are trying to push as the Debian "reproducible builds" effort . It's a new environment variable that can be set with a reference time that should be used throughout the build. It's in "epoch" format: that means it contains a number of seconds since January 1st, 1970, midnight, UTC. The main idea is that when `SOURCE_DATE_EPOCH` is set, it's value replace the "current time of day" whenever it would have been used. So typically statements like "Documentation generated on..." It's already implemented by a handful of tool like `help2man`, Epydoc, Doxygen (in Git), and in the Debian Ghostscript package. We also have submitted patches for GCC, `txt2man`, `libxslt`, and GNU Gettext. And patches are being prepared for more tools.

SOURCE_DATE_EPOCH

- What is it?
  - Environment variable with a reference time
  - Number of seconds since the Epoch (1970-01-01 00:00:00 +0000 UTC)
  - If set, replace "current time of day"
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  - Patches ready for GCC, `txt2man`, `libxslt`, Gettext...
- Set `SOURCE_DATE_EPOCH` in your build system

`https://wiki.debian.org/ReproducibleBuilds/TimestampsProposal`

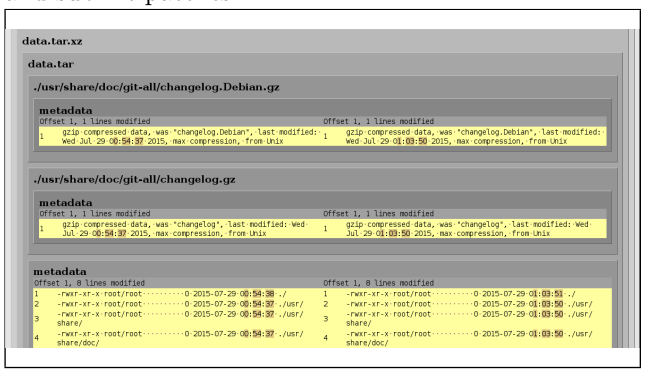
So an easy fix for timestamps is to set `SOURCE_DATE_EPOCH` in your build system.

SOURCE_DATE_EPOCH

- What is it?
  - Environment variable with a reference time
  - Number of seconds since the Epoch (1970-01-01 00:00:00 +0000 UTC)
  - If set, replace "current time of day"
  - Implemented by `help2man`, Epydoc, Doxygen, Ghostscript (in Debian)
  - Patches ready for GCC, `txt2man`, `libxslt`, Gettext…
- Set `SOURCE_DATE_EPOCH` in your build system
- Please add support in any tool writing timestamps

`https://wiki.debian.org/ReproducibleBuilds/TimestampsProposal`

And if it doesn't have the desired effects, please write and submit patches!



But, I'm sorry to say I'm not over with timestamps. Here you can see how the time of the build got recorded by gzip in its headers, and by Tar, as the time of the files in the archive.

Don't record current time (really)

- Archives keep modification times in metadata
- Storing a file can record build time

Example

```
tar -cf product.tar build
```


So most archive formats will keep the file modification times in their metadata. For some rare tools, you can simply tell them to not record medatada, like `gzip` with its `-n` option. But for all others, that means that if your build system creates a new file, and then stores it in an archive, the current time will be recorded in the archive, as we just saw. Several solutions are possible but it also depends on the type of archive we are dealing with.

Don't record current time (really)

- Archives keep modification times in metadata
- Storing a file can record build time
- Solutions:
  - Store an arbitrary value

Example

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


For Tar, we can just use a reference time for all members of the archive.

Don't record current time (really)

- Archives keep modification times in metadata
- 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/*
tar -cf product.tar build
```


Another solution, and this one will work for most archive formats, is to use `touch` to reset the file modification times to a predetermined value.

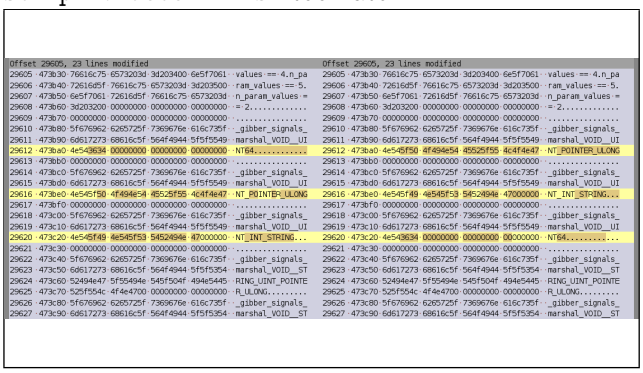
Don't record current time (really)

- Archives keep modification times in metadata
- 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 product.zip build
strip-nondeterminism product.zip
```


For some archive formats, there is always the option of doing post-processing. I will come back to talk about the `strip-nondeterminism` tool later.



Yet another issue. Can you understand what is happening here? There are three functions in this executable. It's always the same three. But sadly, they are not always written in the same order, and the result is not byte-for-byte identical.

Stable order for outputs

- Always output lists in the same 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))
```


So beware of the order of outputs as it needs to be always the same. Everytime there's a list, there might be ordering problems. The typical issue is related to key

ordering in hash tables. To prevent an attacker from consuming a large amount of CPU or memory by attacking the hash function used to store data in a dictionary-like structure (they are called hashes in Perl and in Ruby, or `dicts` in Python), the function is made slightly different on each run by using a random seed. That means that when retrieving the keys in the dictionary, they are likely to be in a different order on every run. The solution to this problem is pretty simple.

Stable order for outputs

- Always output lists in the same order
- Typical issue: key order with hash tables
  `perldoc.perl.org/perlsec.html#Algorithmic-Complexity-Attacks`
- Sort!

Example

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

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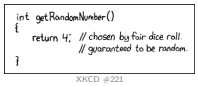
Sort! It's often just a single extra function call that will make the output deterministic.

Avoid (true) randomness

- Randomness is not deterministic



XKCD #221

Example

```
$ gcc -flto -c utils.c
$ nm -a utils.o | grep inline
0000000000000000 n .gnu.lto_.inline.381a277a0b6d2a35
```

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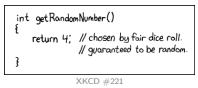
They are more randomness related issues. Unless it's being implemented as suggested by XKCD, any usage of random data by the build process will make the output unreproducible. It's what GCC actually does when "Link-Time Optimization" is enabled. The good news is that computers are very bad at randomness, and what we use are "pseudo-random number generators".

Avoid (true) randomness

- Randomness is not deterministic
- Seed your PRNG from known value
  - Use a fixed value



XKCD #221

Example

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

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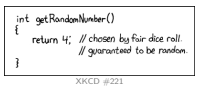
These mathematical functions will take an initial value and from there derive a very very long sequence of numbers which don't look like that have anything in common. So a solution to this problem is to use a predefined value as the seed.

Avoid (true) randomness

- Randomness is not deterministic
- Seed your PRNG from known value
  - Use a fixed value
  - Extract from source code (filename, content hash)



XKCD #221

Example

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

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Sometimes you still need to prevent collisions, and so it might be better to seed the value with a value that can change from one file to another, or from one version of the software to the next. Deriving a filename or a content hash is an obvious answer for these cases.

Define environment variable affecting outputs

- Some environment variables will affect software outputs. E.g:
  - LC_CTIME for time strings
  - LC_CTYPE for text encoding
  - TZ for times

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Another thing you might want to look for is how environment variables might affect outputs. The `date` command on Unix systems might return different results depending on the locale. Files might be written using different character encodings. Various piece of code—hint Gettext—will be affected by the current timezone.

Define environment variable affecting outputs

- Some environment variables will affect software outputs. E.g:
  - LC_CTIME for time strings
  - LC_CTYPE for text encoding
  - TZ for times
- Set them to a controlled value

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If you identify that you are using one of these tools, then set these variables to avoid surprises. One pledge though...

Define environment variable affecting outputs

- Some environment variables will affect software outputs. E.g:
  - LC_CTIME for time strings
  - LC_CTYPE for text encoding
  - TZ for times
- Set them to a controlled value
- *Please don't force the language*

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Please don't blindly overwrite the system language if

you can avoid it. I believe that people should be able to interact with computers in the language they prefer, and they might prefer to get compiler errors in their first language.

Stop recording build system information

- Don't record information about the build system, like:
  - date and time of the build
  - hostname
  - path
  - network configuration
  - CPU
  - environment variables
  - ...

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As a general recommendation, try not to record any information about the build and the build system. Date and time as we already said, but it also goes for the system hostname or its CPU.

Stop recording build system information

- Don't record information about the build system, like:
  - date and time of the build
  - hostname
  - path
  - network configuration
  - CPU
  - environment variables
  - ...
- If you really want to record them, do it outside the binaries

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If you really want to record them, it's best to do it outside of the binaries that will be distributed to users so actual code can be compared more easily. A build log is a perfectly reasonable location to record these kind of information. The version string, not so much. Knowing in which environment a software has been built is far less interesting when you have "reproducible builds".

That's because we are going to use a well-defined environment to perform our builds, as we want users to be able to reproduce it… so they can actually reproduce the build.

What's in a build environment?

- At least: build tools and their specific versions

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So what do we call a build environment? Well, at the very least, it's the tools that are needed to build the software. And in most cases, the actual version that has been used. Compilers for example are being improved all the time with new optimizations. A piece of software built with a newer version of a compiler is quite likely be faster than one built with an older version of the same compiler. That's a good thing, but that means different versions of the same compiler is likely to produce different binaries.

What's in a build environment?

- At least: build tools and their specific versions
- Up to you, depending on the build system:
  - build architecture
  - operating system
  - *build path*
  - *build date and time*
  - ...

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And then, you can decide that other aspects of the environment should be reproduced by users if they want to build your software. If you don't support cross-compiling, mandating a given build architecture is probably a sane thing to do. Or declaring that a given binary can only be created by using FreeBSD. One thing we currently decided for Debian to avoid some pain is to mandate a particular directory where the build should be performed. This avoids problems with paths being recorded in debug symbols, for which we don't have good post-processing tools at the moment. If you use things like `SOURCE_DATE_EPOCH` or `faketime`, you can also declare that a build must be performed using a definite reference time. And basically, it's quite up to you, but you must identify what's in there so users have a chance to produce the same output as the one you are distributing. Once identified you must give a way to reproduce the same environment on their own system.

Build from source

- Build tools affecting the output from source
- Record version / tag / git commit
- Approach used by Coreboot, OpenWrt, *Tor Browser*

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So one way to have users reproduce the tools used to perform the build is simply to have them start by building the right version of these tools from source. That's the approach used by Coreboot, OpenWrt and partially Tor Browser.

Reference distribution

- Use a stable distribution (e.g. Debian, CentOS)
- Record package version
- Hope the old package will stay available / record
- Approach used by Bitcoin, *Tor Browser*

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Another approach, used by Bitcoin and other parts of the Tor Browser build process, is to use a specific version of an integrated operating system. Usually with GNU/Linux using a stable distribution like Debian or CentOS. It needs to stay available for long and to have the least amount of update possible. Better record exact package version, and hope these versions can be later reinstalled.

Virtual machines / containers

- Using a VM saves some problems:
  - Same user
  - Same hostname
  - Same network configuration
  - *Same CPU*
  - ...
- Introduce new things that need to be trusted

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Some things can be quite simplified by using virtual machines or containers. With a virtual machine you can easily perform the build in a more controlled environment. Always using the same user, the same hostname, the same network configuration, you name it. The downside is that it can introduce a lot of software that has be trusted somehow. For example, it's currently not possible to install Debian in a reproducible manner. This makes it harder to compare different installations. We've done some preliminary work, but it's only been about identifying issues so far.

Proprietary operating systems

- Cross-compiling to the rescue!
- For Windows:
  - mingw-w64: build Windows binaries on *nix
  - NSIS (Nullsoft Scriptable Install System)
- For Mac OS X:
  - Used to be quite complicated
    `https://github.com/bitcoin/bitcoin/blob/master/doc/README_osx.txt`
  - Now pretty straightforward with `crosstool-ng`
    `https://bugs.torproject.org/9711#comment:73`
  - Need a non-redistributable SDK extracted from XCode
  - `.dmg` are a bit tricky

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And speaking about trusting operating systems, how can we handle the proprietary ones? It's hard to assess they have not been tampered with. So let's just avoid that path. We actually have free software tools that can build perfectly fine software for Windows and Mac OS X. This is already how it's done for Bitcoin and Tor Browser, so thanks to them for researching this hairy topic. For Windows, `ming-w64` and the Nullsoft Scriptable Install System are both available in Debian. This is actually how we are building the application that can launch the `debian-installer` on Windows. For Mac OS X, it used to be quite hackish, but it's getting better thanks to the work done by Ray Donnelly. You will need to use a non-redistributable part, although it's provided by Apple after free registration, from XCode to build the toochain. Software from Mac OS X is often distributed as disk images which can be created under GNU/Linux, but it kinda requires 3 different tools at the moment. Hopefully if more people start doing this, the whole process is likely to get improved in the future.

So, great! We now have defined what's our canonical build environment. How do we distribute it to our users alongside our binaries and source code?

Good ol'Makefile

- Download known toolchain archives
- Compare reference checksums
- Build and setup
- Coreboot: `make crossgcc`

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If the environment is only about build tools, maybe the easiest way is just to add an extra target to your `Makefile`. For example, building Coreboot almost mandate to first run `make crossgcc`. This will download known archives for GCC, `binutils` and others, compare the archives with reference checksums, and proceed to build them. And it's these tools that are going to be used by the rest of the build process.

Check-in everything

- Check-in all the toolchain source code in VCS
- Approach used for the base system in *BSD, and Google
- Make sure everything is checked in (*use sandbox on Linux*)
- Recently open-sourced: Bazel
  `http://bazel.io/`
- Can be hard to ask everyone to download everything all the time

A more radical extension to the former approach is to actually check everything in your version control system. Everything as in the source of every single tool. That's how it's working when you are "building the world" on BSD-like systems. That's also how Google is doing it internally. To make absolutely sure that everything is checked-in, you can even use "sandboxing" mechanisms to avoid the risk of running a tool that has not been built from source. Google recently started open-sourcing the tool they use internally to drive such large scale builds under the name Bazel. So despite its syntax that I personally find hard to read, it's probably worth checking out. But if you are not working in a corporate environment, or on a fully integrated operating system, it might be hard to push. You don't really want to ask everyone to download and build every possible version of GCC every time they would like to build a piece of code.

Ship the toolchain as a build product

- Make the toolchain as a build product
- OpenWrt:
  `http://wiki.openwrt.org/doc/howto/obtain.firmware.sdk`

Example

```
$ wget https://downloads.openwrt.org/…/14.07/…OpenWrt-SDK-atheros-….tar.bz2
$ svn export svn://…/branches/packages_14.07/utils/xz package/xz
$ make package/xz/compile
```


As a middle ground, OpenWrt offers an "SDK" that can be downloaded alongside their system images which contains everything that is needed to build—or rebuild—extra packages. To close the loop, as the SDK becomes another build product, it has to be possible to build it reproducibly.

Gitian

- Used by Bitcoin, Tor Browser
- Drives LXC or KVM
- "Descriptors" describing the build using:
  - Base distribution
  - Packages
  - Git remotes
  - Other input files
  - Build script

Resources

```
https://gitian.org/
https://github.com/bitcoin/bitcoin/blob/master/doc/gitian-building.md
https://github.com/bitcoin/bitcoin/blob/master/contrib/gitian-descriptors/
```


Gitian is the tool used by Bitcoin and the Tor Browser. It either drives a Linux container using LXC, or a virtual machine using KVM. Gitian takes "descriptors" as input which tells which base GNU/Linux distribution to use, which packages to install, which Git remotes must be fetched, any other input files, and a build script to be run with all of that. As explained earlier, using a virtual machine helps to get rid of several extra variations that can happen from one system to the next. But this is more complicated to setup for users.

Docker

- Provide a way to describe specialized Linux container images
- Build in a controlled environment
- Docker images can be addressed with a hash of their content
- Bazel has support to build Docker images reproducibly

`https://github.com/tianon/gosu/blob/master/Dockerfile`

```
FROM golang:1.4-cross
[…]
# disable CGO for ALL THE THINGS (to help ensure no libc)
ENV CGO_ENABLED 0
COPY *.go /go/src/github.com/tianon/gosu/
WORKDIR /go/src/github.com/tianon/gosu
RUN GOARCH=amd64 go build -v -ldflags -d -o /go/bin/gosu-amd64
```


Making containers easy to setup and use is exactly the problem that Docker is trying to solve. `Dockerfile`s are used to describe how to create a container, and how applications can be run in there. This specific example is how a tool often used in Docker images, `gosu` is built. Using the reference container made available to build Go applications, it then installs the necessary dependencies, and calls the Go compiler in that environment which should be pretty much the same all the time. To be sure that the base compiler is the same, one could use the fact that Docker images can actually be addressed by a hash of their content. Another option is to build the Docker image itself in a reproducible manner, and from what I read in the documentation, Bazel—mentioned earlier— is able to do this.

Vagrant

- Drive VirtualBox using Ruby and other scripts
- Build in a controlled environment
- Also works under OS X and Windows

`https://www.vagrantup.com/`

Vagrant is another tool, written in Ruby, that can drive virtual machines with VirtualBox. It can also be used to get a controlled build environment. The upside of Vagrant and VirtualBox is that they works on Mac OS X and Windows, and so this might help more users to actually check that a build has not been tempered with.

Debian .buildinfo

- Tie in the same file:
  - Sources
  - Generated binaries
  - Packages used to build (with specific version)
- Can be later processed to reinstall environment
- All versions are available from `snapshot.debian.org`

For Debian, we decided for another path. We defined a new control format, called `.buildinfo` where we list the sources, the generated binaries, and every packages that were installed in the system when these binaries were built. It means that we can easily reproduce the build environment by reinstalling each package with the specific version that we had recorded. We can do that because Debian has a service called "snapshot" which records every binary package ever uploaded to the Debian archive, so older versions of a given package stay available even when they have been superseded by a later one.

Example .buildinfo

```
Format: 1.9
Build-Architecture: amd64
Source: txtorcon
Binary: python-txtorcon
Architecture: all
Version: 0.11.0-1
Build-Path: /usr/src/debian/txtorcon-0.11.0-1
Checksums-Sha256:
 a26549d9…7b 125910 python-txtorcon_0.11.0-1_all.deb
 28f6bcbe…69 2039 txtorcon_0.11.0-1.dsc
Build-Environment:
 base-files (= 8),
 base-passwd (= 3.5.37),
 bash (= 4.3-11+b1),
 …
```


Here's an example of what a `.buildinfo` looks like. So you can see the build architecture, checksums of source—that's the `.dsc`— and the binary packages, the build path, and all the packages involved. Hopefully they will be soon available on Debian mirrors and users should then be able to simply call a script to re-do the environment and then the build.

It's been two years we've been working on this in Debian. We're not totally there yet, but here's still some tips to share.

Testing for variations

- Build a first time
- Save the result
- Perform change(s) to the environment
- Build a second time
- Compare results

If users are the ones that detects that changes in the environment affect the build, it's going to raise a lot of false alarms. So better perform tests ahead. The basic idea we are currently using in Debian is that we build a first time, keep the result aside, change various stuff in the environment, perform a second build, and then compare the results.

reproducible.debian.net

- Continuous test system driven by Jenkins
- Bad-ass hardware sponsored by ProfitBricks
- Tests about 1300 Debian source packages per day on average
- Results are visible on a website
- Other projects: Coreboot, OpenWrt, *yours?*

PROFITBRICKS
The IaaS-Company.

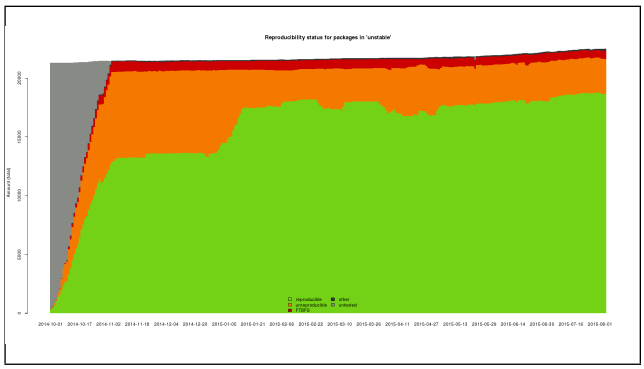
Based on this, Holger Levsen, now helped by Mattia Rizzolo, setup a continuous test system driven by Jenkins. Thanks to ProfitBricks for the crazy bad ass hardware as it's able to perform 1300 tests—that means building 1300 packages twice—every day on average. The results are then put in a database and browsable on the web. The system has been recently extended to other projects and we are currently performing tests for Coreboot and OpenWrt. Work has also started to test FreeBSD and NetBSD… Holger is at the camp, so please talk to him if you want to ask about your projects!

Variations on reproducible.debian.net

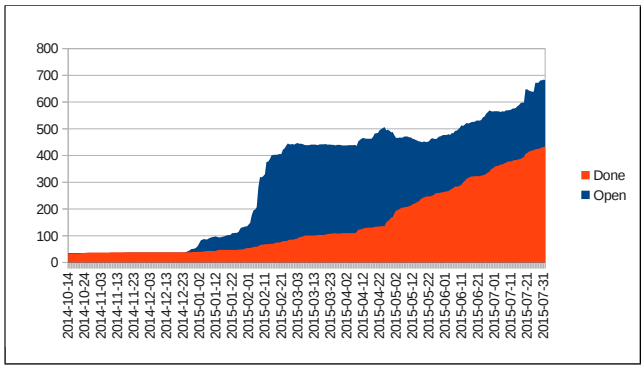
variation	first build	second build
hostname	`jenkins`	`i-capture-the-hostname`
domainname	`debian.net`	`i-capture-the-domainname`
env TZ	`GMT+12`	`GMT-14`
env LANG	`en_GB.UTF-8`	`fr_CH.UTF-8`
env LC_ALL	not set	`fr_CH.UTF-8`
env USER	`pbuilder1`	`pbuilder2`
uid	1111	2222
gid	1111	2222
UTS namespace	shared with the host	*modified using `/usr/bin/unshare --uts`*
kernel version	Linux 3.16.0-4-amd64	Linux 2.6.56-4-amd64
umask	0022	0002
CPU type	same for both builds *(work in progress)*	
year, month, date	same for both builds *(work in progress)*	
hour, minute	hour is usually the same… usually, the minute differs… *(work in progress)*	
everything else	*is likely the same…*	

To give you an overview, these are all the variations we are currently performing between the first build and the second one. So hostname, domain name, timezone (see how we use timezones that are more than 24 hours apart so that we get a different day), the language, general locale settings, username, user id, group id, network namespace, kernel version, umask… and pretty soon we'll have the second run on a different machine that will have

a different number of cores, a different date, and maybe a different filesystem. Hopefully, we'll then be covering it all, but time will tell.



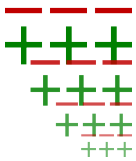
I didn't want to make this talk too much about the Debian project, but just to give you a quick view on how we are doing. Some crucial patches are still experimental and not in the main Debian archive. But with our experimental toolchain, our tests are now positive for more than 80



And here might be a more accurate view of the progress we are making every day as Debian maintainers integrate the patches that we are submitting.

Debugging problems: diffoscope

- Examines differences **in depth**
- Outputs HTML or plain text showing the differences
- Recursively unpacks archives
- Seeks human readability:
  - uncompresses PDF
  - disassembles binaries
  - unpacks Gettext files
  - … *easy to extend to new file formats*
- Falls back to binary comparison

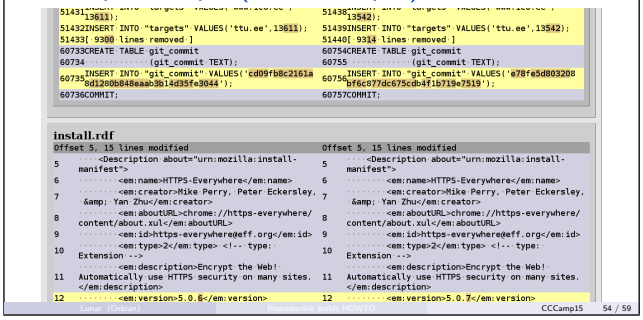


`http://diffoscope.org/`

(formely known as debbindiff)

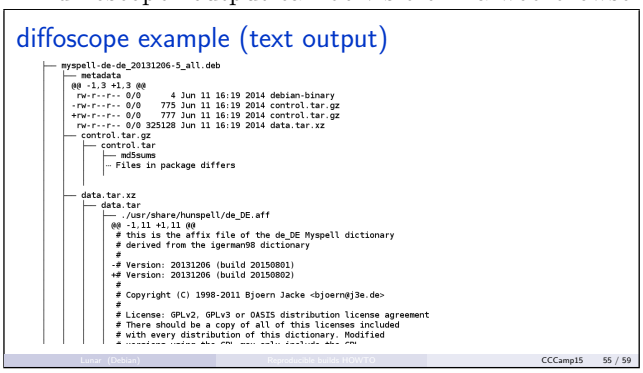
That's also because we came up with a tool that helped us understand issues. Comparing two different compressed archives is not going to help you understand much of why they are different. It's every files in these archives that need to be compared. So that's why we came up with "diffoscope". It will recursively unpack archives, and for binary files, try to get a human readable representation before comparing them. It will fallback to comparing hexdumps if the bytes are different but no differences show up in the human readable representation. "diffoscope" is designed to be extensible and has now grown way beyond just being a tool for Debian packages. It also supports RPM, ISO images, or squashfs filesystems.

diffoscope example (HTML output)



"diffoscope" output can be visible in a web browser.

diffoscope example (text output)



Or in plain text which it might be easier to post-process or share.

strip-nondeterminism

- Normalizes various file formats
- Currently handles:
  - ar archives (`.a`)
  - gzip
  - Java jar
  - Javadoc HTML
  - Maven `pom.properties`
  - PNG
  - ZIP archives
  - … *extensible to new formats*
- Written in Perl (like `dpkg-dev`)

`git://git.debian.org/reproducible/strip-nondeterminism.git`

Another tool we came up in Debian is `strip-nondeterminism`, originaly written by Andrew Ayer. It is meant to be a central place to perform post-processing on various file formats to remove bits of non-determinism. It already handles several file formats and should be easily extensible to more. It is written in Perl, like the other tools you need to create Debian packages, to avoid adding an extra build dependency.

Resources

- Reproducible Builds HOWTO (*work in progress*)
  `https://reproducible.debian.net/howto/`

I'm ending with a couple more resources. We have started to write an HOWTO which should contain more or less what I've been telling you for the past forty minutes. Contributions from all projects are highly welcome.

As I said, “reproducible builds” should become the norm, and it would be great to have reference documentation that can be widely shared and used.

Resources

- Reproducible Builds HOWTO (*work in progress*)
  `https://reproducible.debian.net/howto/`
- Debian “Reproducible Builds” wiki
  `https://wiki.debian.org/ReproducibleBuilds`

We’ve been collecting a lot of information about reproducibility issues on the Debian wiki. Some are pretty specific to Debian, but there’s a lot to learn. We’ve also been collecting rationales, media mentions, and other goodies.

Resources

- Reproducible Builds HOWTO (*work in progress*)
  `https://reproducible.debian.net/howto/`
- Debian “Reproducible Builds” wiki
  `https://wiki.debian.org/ReproducibleBuilds`
- Diverse Double-Compilation
  `http://www.dwheeler.com/trusting-trust/`

Last but not least, I’d like to mention David A. Wheeler’s work on Diverse Double-Compilation. Often when I explain the idea of “reproducible builds”, someone comes up asking “but how can you be sure that your compiler has not been backdoored so that the next time it builds a compiler it will not insert another backdoor?” This is also known as the “trusting trust” attack from Ken Thompson that was mentioned in the Snowden document. So David refined (and also did a formal proof) that we can answer this question using a process that is called Diverse Double-Compilation. I’ll try to sum it up quickly: you need two compilers, with one that you somehow trust; then you build the compiler under test twice, once with each compiler, and then you use the compilers that you just built to build the compiler under test again. If the output is the same, then no backdoors. But for this scheme to work, you need to be able to compare that both build outputs are the same. And that’s exactly what we are enabling when having reproducible builds.

I’m done. I sincerely hope that this short lecture will make you want to provide reproducible builds. As I said, I really think we all need this to become the norm. Thanks for listening. And I now will be happy to take questions.

Thanks!

- Debian “Reproducible Builds” team
  (you are just **so** awesome!)
- Mike Perry, Georg Koppen, David A. Wheeler
- Linux Foundation and the Core Infrastructure Initiative

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`4C79 8382 C95C 2902 3DF9`

clothes: Elhonna Sombrefeuille — hair: igor