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Comparing Next-Generation Container Image Building Tools

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Who am I

- **Software Engineer at NTT**
- **GitHub: @AkihiroSuda**
- **Twitter: @_AkihiroSuda_**

- ~~**Docker**~~ **Moby core maintainer**
  - In April 2017, Docker [as a project] transited into Moby
  - Now Docker [as a product] has been developed as one of downstreams of Moby

Who am I

- **BuildKit initial maintainer**
  - Next-generation `docker build`
- **containerd maintainer**
  - Industry-standard container runtime
  - Can be used as a Docker-replacement for Kubernetes
- **Docker Tokyo Community Leader (meetup organizer)**
  - https://dockerjp.connpass.com/

Agenda

- **Problems of `docker build`**
- **New image builder tools**

BuildKit	img	Buildah	umoci&orca
kaniko	Bazel	Source-to-Image	Metaparticle

- **Comparison & Evaluation**
- **CBI: "Container Builder Interface"**

Introduction to Dockerfile

- **Shell-script-like language for building Docker container images**

- **Each of the lines is cached as a Copy-on-Write filesystem layer, e.g. overlayfs**

```
FROM golang:1.10
COPY . /go/src/github.com/foo/bar
RUN  go build -o /bar github.com/foo/bar
```

```
mount -t overlay \
 -o lowerdir=0,upperdir=1 ..
```

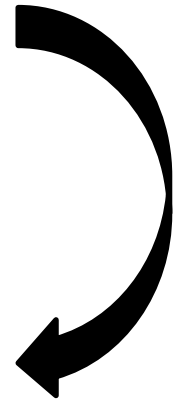
```
mount -t overlay \
 -o lowerdir=1,upperdir=2 ..
```

Introduction to Dockerfile

- **Supports transferring files between stages, starting with Docker 17.05**
  - Effectively reduces the size of the final image

```
FROM golang:1.10 AS foobar
COPY . /go/src/github.com/foo/bar
RUN  go build –o /bar github.com/foo/bar

FROM alpine:3.7
COPY --from=foobar /bar /
```



copy "bar" to the final stage

Introduction to `docker build`

- **Docker-integrated tool for building images using Dockerfile**
  - Requires Docker daemon to be running

- **Similar to `docker run`, but some features are intentionally removed for security reason**
  - No volumes (`docker run -v`, `docker run --mount`)
  - No privileged mode (`docker run –-privileged`)

Problem: inefficient caching

- **Modifying a single line always invalidates the caches of the subsequent lines**
  - N-th line is assumed to always depend on the (N-1)-th line

```
FROM    debian
EXPOSE 80
RUN     apt update && apt install -y HEAVY-PACKAGES
```

Modifying this line always invalidates the apt cache due to the false dependency

- **A user needs to arrange the instructions carefully for efficient caching**

Problem: no concurrency

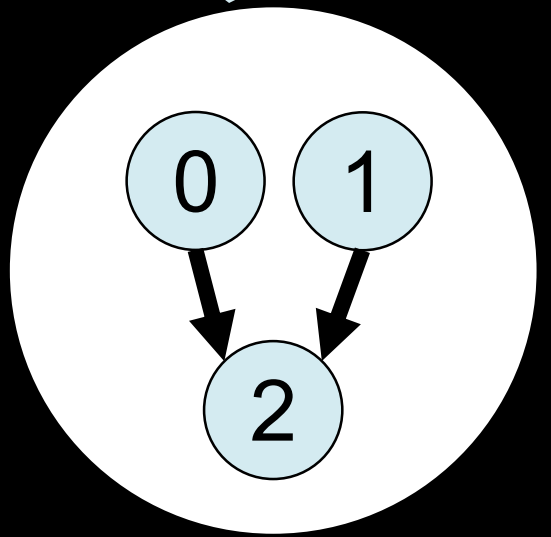
- **A multi-stage Dockerfile has DAG structure**

```
FROM golang AS stage0
...
RUN go build –o /foo ...

FROM clang AS stage1
...
RUN clang –o /bar ...

FROM debian AS stage2
COPY --from=stage0 /foo /usr/local/bin/foo
COPY --from=stage1 /bar /usr/local/bin/bar
```

Directed Acyclic Graph
has concurrency



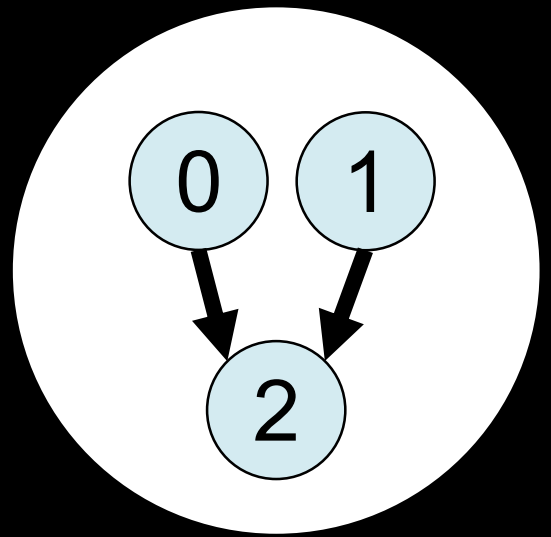
Problem: no concurrency

- **A multi-stage Dockerfile has DAG structure**

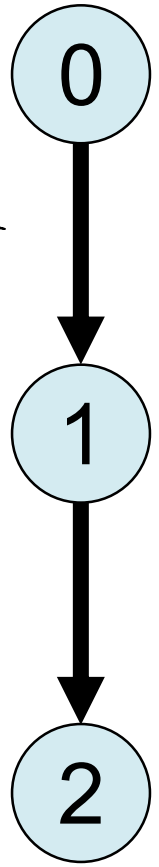
```
FROM golang AS stage0
...
RUN go build –o /foo ...

FROM clang AS stage1
...
RUN clang –o /bar ...

FROM debian AS stage2
COPY --from=stage0 /foo /usr/local/bin/foo
COPY --from=stage1 /bar /usr/local/bin/bar
```



Actual `docker build` implementation (Sequential)



Problem: inaccessible to private assets

- **No safe way to access private assets (e.g. Git repos, S3) from build containers**
- **Copying credentials using `COPY` can leak the credential accidentally**
  - Needs to be carefully used with either multi-stage or `--squash`

```
FROM ...
COPY id_rsa ~/.ssh
RUN  git clone ssh://...
RUN  rm -f ~/.ssh/id_rsa
```

The key still remains in the layer!

- **Env vars are vulnerable to accidents as well**

Other problems

- **Cannot be executed without root privileges**
  - Important for building images on Kubernetes
- **Cannot preserve compiler caches due to lack of volumes**
- **Unreproducible builds**
  - Non-deterministic command executions
  - *Left-pad* issue
- **Dockerfile can be too complex and hard to maintain**

Solutions

BuildKit	img	Buildah	umoci & orca
kaniko	Bazel	Source-to-Image	Metaparticle

- **And more!**
  - FTL, Smith, Ansible Container...
- **Some of them still use Dockerfile, others not**
- **No "silver bullet" solution**

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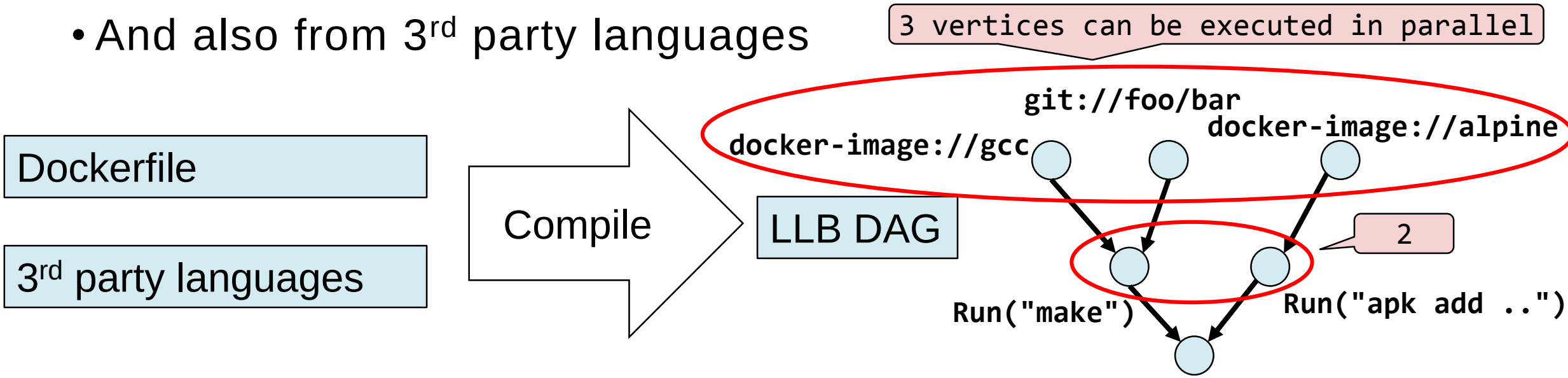
BuildKit: next-generation `docker build`

- **Uses DAG-style low-level intermediate language called LLB**
  - Accurate dependency analysis and cache invalidation
  - Vertices can be executed in parallel

- **LLB can be compiled from Dockerfile**
  - And also from 3rd party languages



https://github.com/moby/buildkit

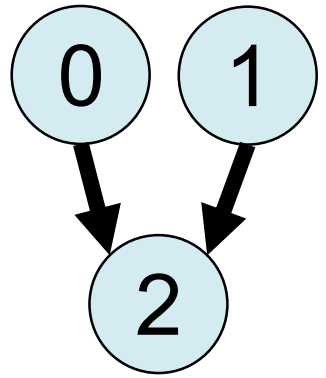
BuildKit: next-generation `docker build`

- **DAG structure of LLB can be described using multi-stage Dockerfile**

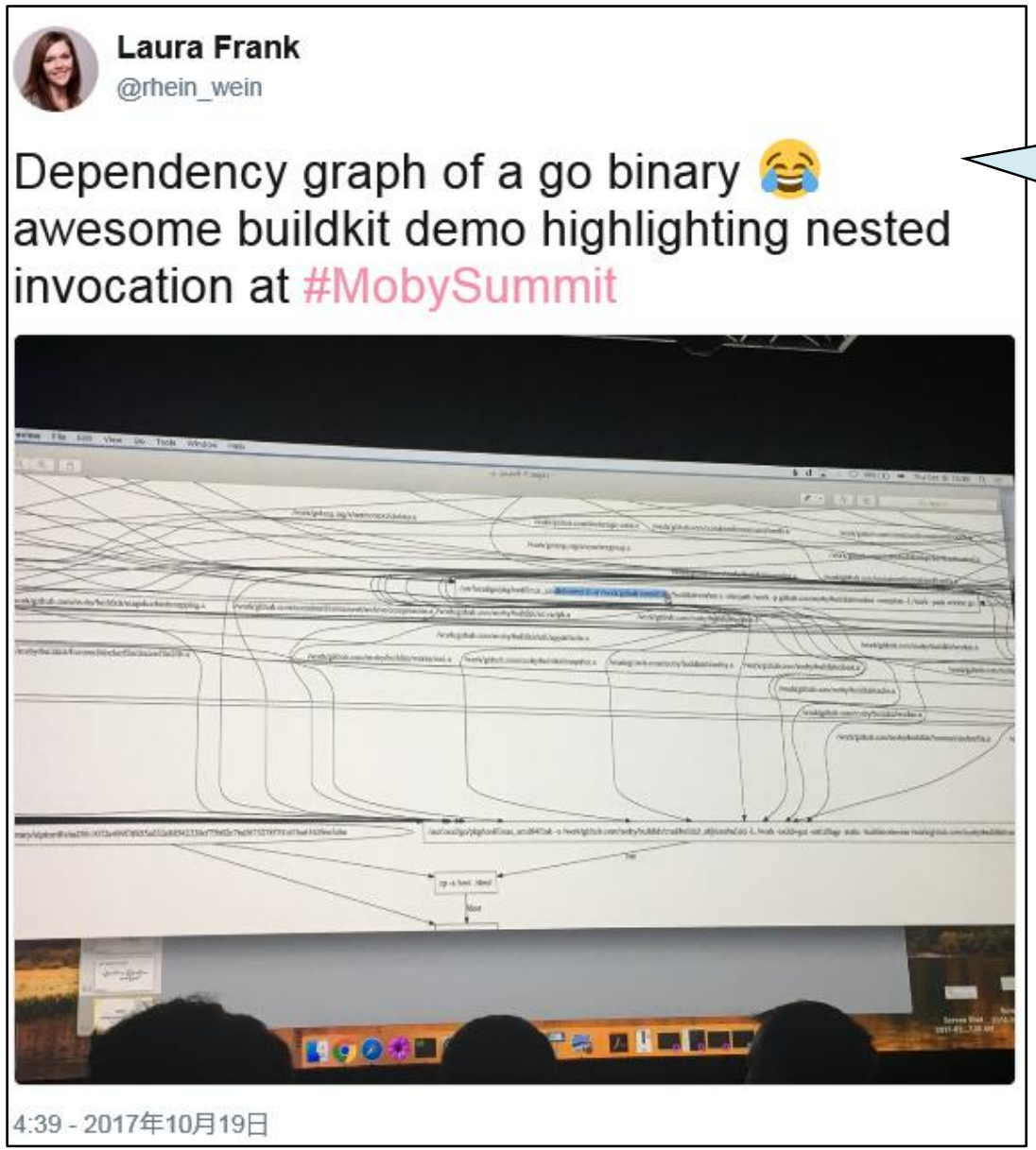
```
FROM golang AS stage0
...
RUN go build –o /foo ...

FROM clang AS stage1
...
RUN clang –o /bar ...

FROM debian AS stage2
COPY --from=stage0 /foo /usr/local/bin/foo
COPY --from=stage1 /bar /usr/local/bin/bar
```



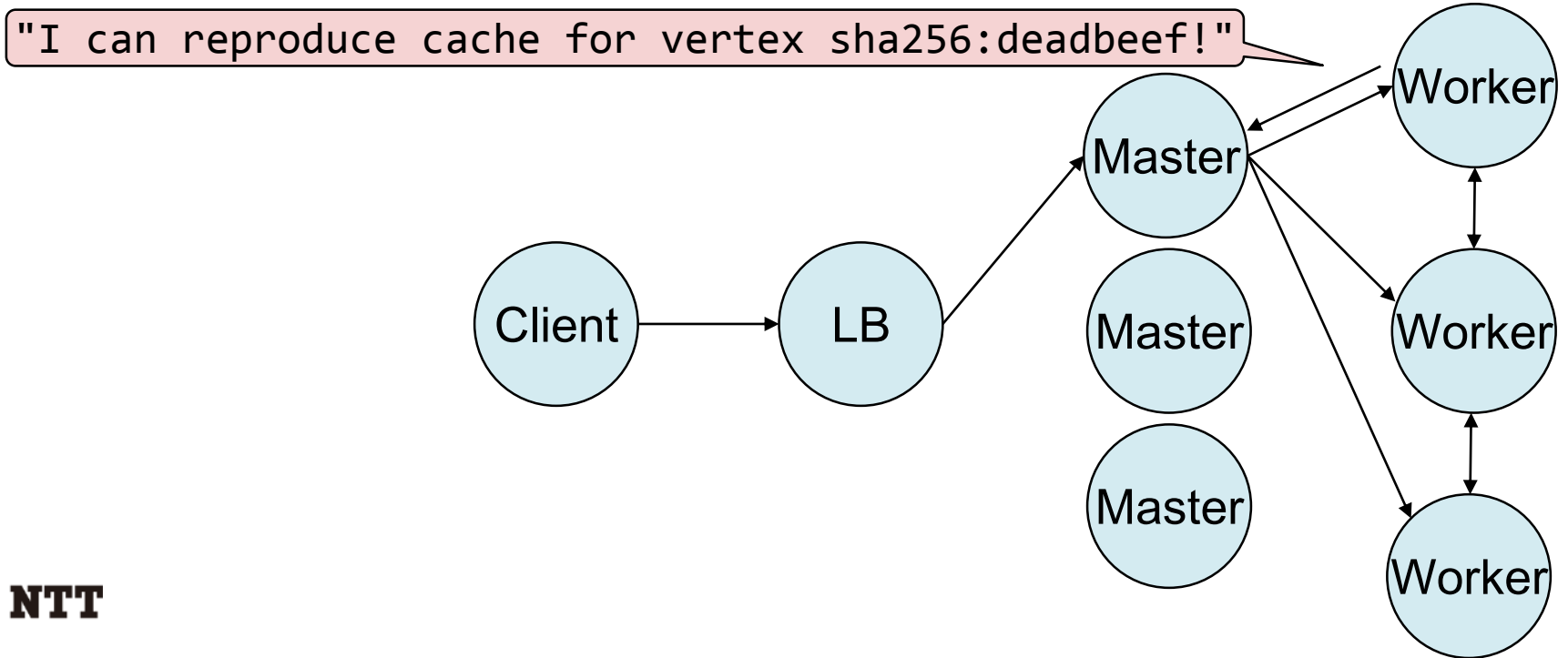
BuildKit: next-generation `docker build`



Can be also used for building non-container artifacts

BuildKit: next-generation `docker build`

- **Distributed mode is also on plan (#224, #231)**
  - A worker tells the master its loadavg and LLB DAG vertex cache info
  - The master choose the worker for each of the LLB DAG vertices using the info from the workers



BuildKit: next-generation `docker build`

- **Experimental support for rootless mode**
  - Runs everything including BuildKit itself as an unprivileged user, using `user_namespaces(7)`
    - Protect the system from potential bugs of BuildKit/containerd/runc.
    - Also useful for HPC users
    - Requires `newuidmap(1)` and `newgidmap(1)` with SUID bit for `apt`
  - No patch for runc is needed since June 2018
  - Don't confuse this with `dockerd --userns-remap`
    - `dockerd --userns-remap` still requires `dockerd` itself to be executed as the root

BuildKit: next-generation `docker build`

- **Rootless BuildKit can be executed inside Docker and Kubernetes**
  - But requires `--privileged` for let `RUN` containers mount `/proc`
    - Will be fixed soon via moby/moby#36644 and kubernetes/kubernetes#64283
    - Still safe because BuildKit works as an unprivileged user

```
...
USER penguin
ENTRYPOINT ["rootlesskit", "buildkitd"]
```

RootlessKit: shim for setting up user NS and mount NS
https://github.com/AkihiroSuda/rootlesskit

BuildKit: next-generation `docker build`

- **Plan to support "privileged" build as well**
  - likely to use libentitlement (#238)
  - e.g. `buildctl build --entitlements=security.unconfined` for privileged build
  - potential use-cases: GPU, FUSE, ...

BuildKit: next-generation `docker build`

- **Supports non-standard Dockerfile "syntax", e.g. `RUN --mount`**

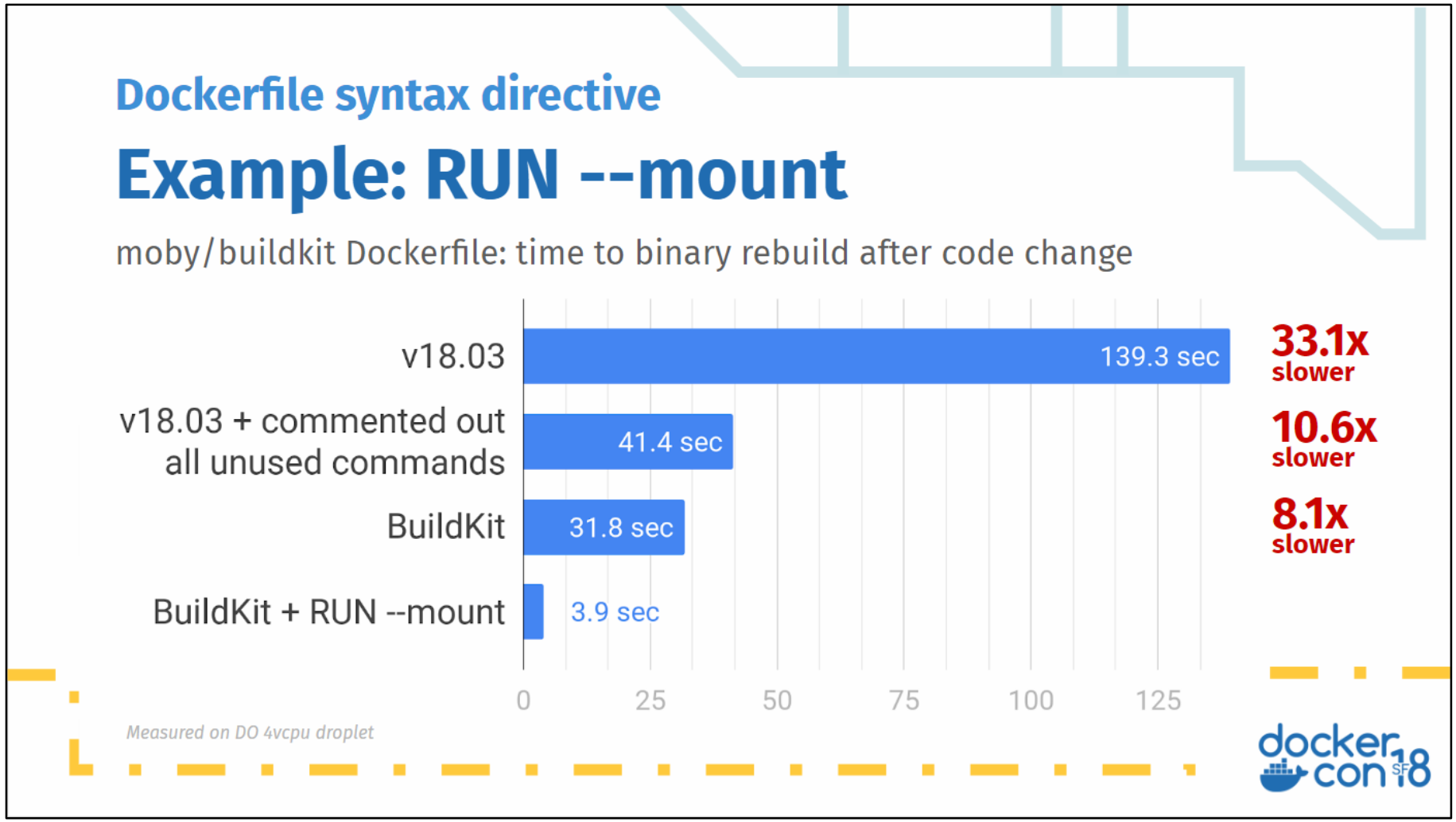
```
# syntax = tonistiigi/dockerfile:runmount20180610
...
RUN --mount=target=/root/.cache,type=cache go build
```

Cache mount can be useful for compillers (e.g. Go) and package managers (e.g. apt)

- **`RUN --mount` will also support SSH agent socket file and secret files (#262)**

BuildKit: next-generation `docker build`

- Benchmark result (from Tonis's slide: https://t.co/aUKqQCVmXa)



BuildKit: next-generation `docker build`

- **Will be integrated to Moby & Docker 18.06 (moby/moby#37151)**
  - No change on the `docker build` command line but you need to set `DOCKER_BUILDKIT=1`
  - Will be released by the end of this month

- **Also adopted by OpenFaaS Cloud**
  - https://github.com/openfaas/openfaas-cloud
  - "GitOps for your functions with native GitHub integrations"

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BuildKit: next-generation `docker build`

- **Developed under Moby's open governance**
  - But Dockerfile-to-LLB compiler is planned to be moved to Docker, Inc.'s repo (#425)
    - Dockerfile specification is maintained by Docker, Inc.
  - LLB allows implementing non-Dockerfile languages
    - Any idea for new language?

img: daemonless BuildKit

- **Created by Jessie Frazelle (Microsoft)**

- **Uses BuildKit as a library but daemonless and has Docker-like CLI**
  - Currently no support for running multiple `img` instances with the same cache directory (#92)

- **Rootless mode by default**

```
$ img build -t example.com/foo .
$ img push example.com/foo
$ img save example.com/foo | docker load
```

https://github.com/genuinetools/img

Buildah: Red Hat's daemonless `docker build`

buildah

- **Created by Red Hat**
  - Officially included in RHEL since RHEL 7.5

- **Supports Dockerfile, but `buildah run` and `buildah commit` are supported as well**
  - as in `docker run` and `docker commit`, without Dockerfile

- **Daemonless**
  - Can be used as a backend of `podman build`
    - Podman: Red Hat's daemonless and swarmless Docker-like tool

https://github.com/projectatomic/buildah

Buildah: Red Hat's daemonless `docker build`

- **Supports secret volume**
  - But configuration is globally scoped
    - `/etc/containers/mounts.conf`
      - e.g. `/usr/share/rhel/secrets:/run/secrets` for allowing all Buildah containers to access RHEL subscriptions
      - Seems to have usability and security concern for other use-cases

- **Rootless mode is planned (#386)**

Buildah: Red Hat's daemonless `docker build`

- **Cache for Dockerfile instructions is not supported but planned (#601)**

- **Parallelization is also planned (#633)**
  - And distributed execution as well

Umoci & Orca: the first rootless and daemonless image builder

- **Created by Aleksa Sarai (SUSE)**

- **Umoci: Umoci modifies Open Container images**
  - Unpacks and repacks OCI Image Spec archives (tar+gz and JSON) into/from OCI Runtime Spec bundles (directories)

  - "Pure"-Rootless and daemonless
    - Does not require setting up subuids/subgids (which require SUID binary) for unpacking archives that have multiple UIDs/GIDs
      - Uses `user.rootlesscontainers` xattr instead of `chown(2)`

https://github.com/openSUSE/umoci
https://github.com/cyphar/orca-build

Umoci & Orca: the first rootless and daemonless image builder

- **Orca: Umoci-based image builder with support for Dockerfile**
  - Can be used with runROOTLESS for images that require multiple UIDs/GIDs (typically Debian/Ubuntu apt)
    - https://github.com/rootless-containers/runrootless
    - Emulates several system calls using `ptrace(2)` and `user.rootlesscontainers` xattr values (which are set by Umoci)
    - No SUID binary is required (but slow)
  - Multi-stage Dockerfile and caching are not supported at the moment
  - Planned to be integrated into Umoci
    - https://twitter.com/lordcyphar/status/987668301890207744

kaniko: "containerless" rootless builder

- **Created by Google**

- **Kaniko itself needs to be executed in a container, but does not require `--privileged`**
  - Execute `RUN` instructions within Kaniko's rootfs and namespaces
    - i.e. `RUN` instructions are executed without creating containers
  - Excludes kaniko itself's binary and configuration files on packing the rootfs archives
  - Seems inappropriate for malicious Dockerfiles due to lack of isolation (#106)

https://github.com/GoogleCloudPlatform/kaniko

Non-Dockerfile based tools

- **Bazel: Google's generic build system**
  - Not specific to containers
  - `rules_docker` can build Docker images, but equivalent of `RUN` instruction is intentionally omitted due to poor reproducibility

```
# https://github.com/bazelbuild/rules_docker#container_image
container_image(
    name = "app",
    base = "@java_base//image",
    files = ["//java/com/example/app:Hello_deploy.jar"],
    cmd = ["Hello_deploy.jar"]
)
```

Non-Dockerfile based tools

- **Source-to-Image: Red Hat OpenShift's build system**
  - Application developers don't need to write any file for building images
  - S2I base images contain scripts for building applications in the language-specific way
    - e.g. `centos/python-35-centos7` for Python 3.5
  - Previous versions depended on Docker, but recent version can produce Dockerfiles that can be built by other tools

Non-Dockerfile based tools

- **Metaparticle: library for cloud-native apps on Kubernetes**
  - Supports .NET, Go, Java, JS, Python, Ruby, Rust

```
from metaparticle import Containerize
@Containerize(package={'repo': 'foo/bar', ...)
def main():
    ...
```

  - Hard to change the target repository without editing source codes
    - Or implementing a new library on top of Metaparticle
  - Also provides service-related features
    - e.g. sharding HTTP requests based on URL

Non-Dockerfile based tools

- **FTL**
  - Similar to S2I but only for Node.js, Python, and PHP
- **Smith**
  - Supports Oracle's "Microcontainer Manifest"
- **Ansible Container**
  - Supports Ansible Playbook
  - README says "*no longer under active development*"

Comparison across Dockerfile-based tools

	Docker	BuildKit	img	Buildah	Orca	kaniko
Instruction cache	Limited	✓	✓			
Parallelization		✓	✓	Planned		
Distributed execution		Planned		Planned		
Daemonless		As a library	✓	✓	✓	✓
Rootless		✓ 1	✓ 1	Planned	✓ 2	✓ 3

1 Requires SUID binary for apt

Comparison across Dockerfile-based tools

	Docker	BuildKit	img	Buildah	Orca	kaniko
Instruction cache	Limited	✓	✓			
Parallelization		✓	✓	Planned		
Distributed execution		Planned		Planned		
Daemonless		As a library	✓	✓	✓	✓
Rootless		✓ 1	✓ 1	Planned	✓ 2	✓ 3

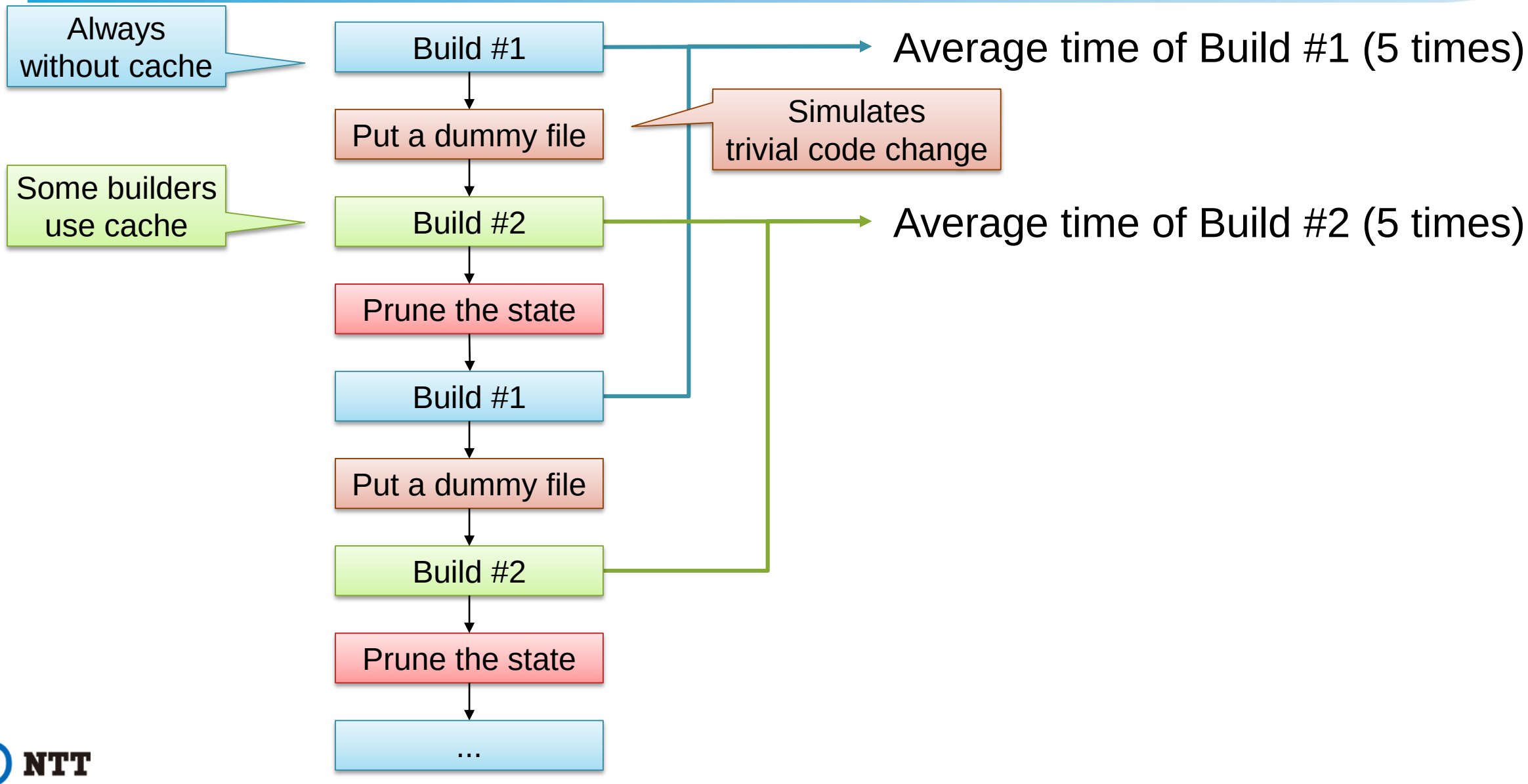
2 No SUID required but slow

Comparison across Dockerfile-based tools

	Docker	BuildKit	img	Buildah	Orca	kaniko
Instruction cache	Limited	✓	✓			
Parallelization		✓	✓	Planned		
Distributed execution		Planned		Planned		
Daemonless		As a library	✓	✓	✓	✓
Rootless		✓ 1	✓ 1	Planned	✓ 2	✓ 3

3 Executable in containers without `--privileged` but still has security concern

Benchmark



Benchmark

- **Benchmark script is available**
  - https://github.com/AkihiroSuda/buildbench
  - Supported tools: Docker, Buildkit, img, Buildah, Kaniko
  - Everything is containerized
  - Builders (except Kaniko) are configured to use overlayfs

- **Tested on Travis CI (June 19, 2018)**
  - Logs (contains version info and raw data): https://travis-ci.org/AkihiroSuda/buildbench/builds/393967682
    - See also https://github.com/AkihiroSuda/buildbench/issues/5
  - 2 bursted vCPUs, 7.5GB RAM

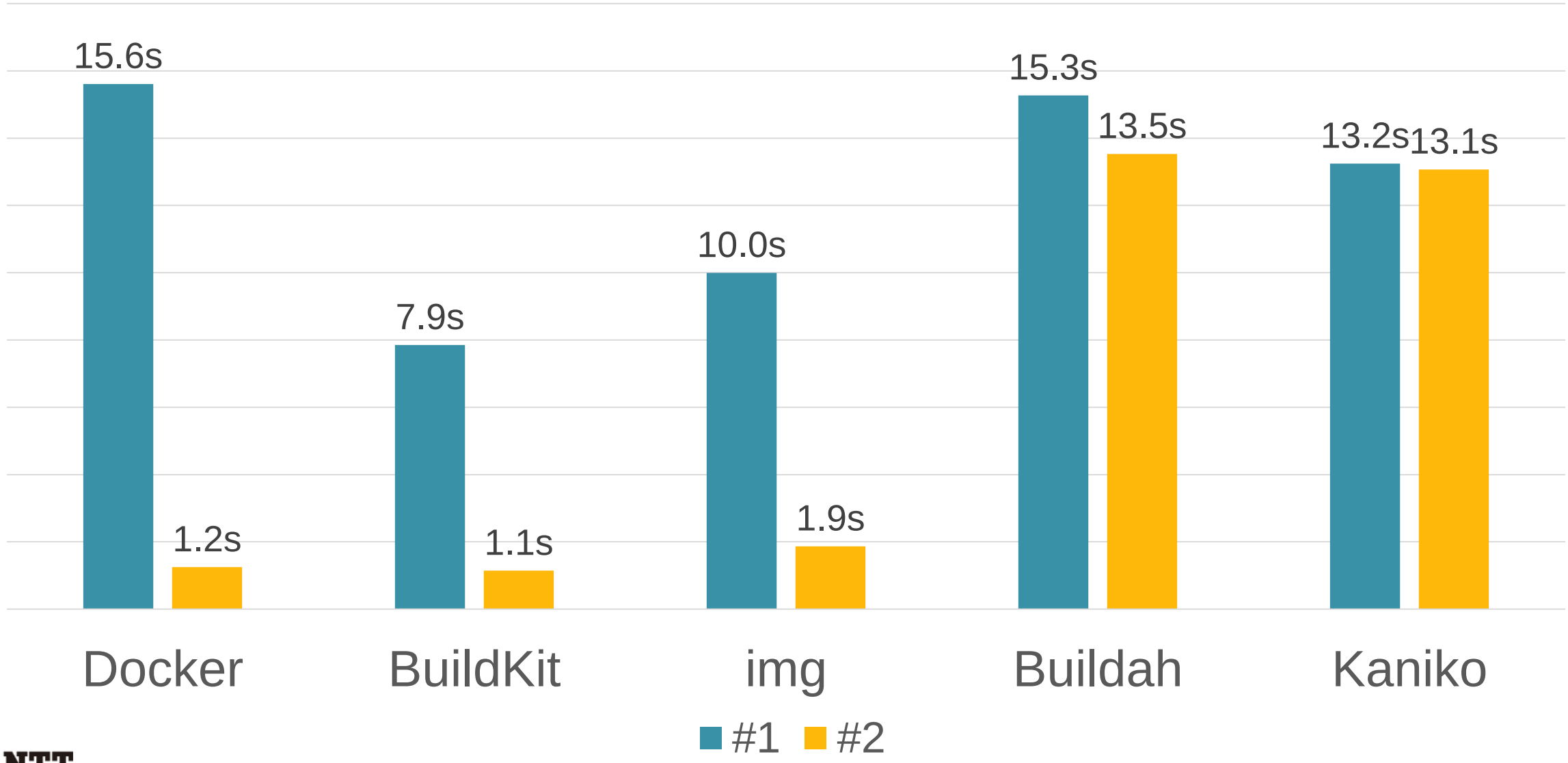
Benchmark: examples/ex01

```
FROM alpine AS buildc
RUN apk add --no-cache build-base
RUN echo ... > hello.c
COPY . /foo
RUN gcc -o /a.out /hello.c

FROM alpine AS buildgo
RUN apk add --no-cache build-base
RUN apk add --no-cache go
RUN echo ... > hello.go
RUN go build -o /a.out /hello.go

FROM alpine
COPY --from=buildc /a.out /hello1
COPY --from=buildgo /a.out /hello2
```

Only the cache for the next line SHOULD be invalidated on modification of the build ctx

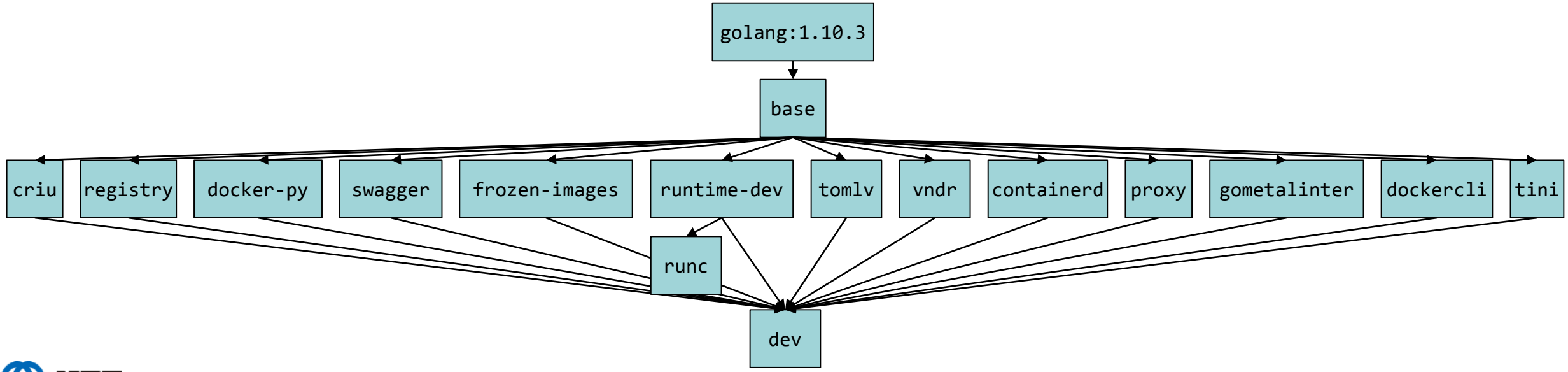
`apk add build-base` SHOULD NOT be executed twice

Benchmark result: examples/ex01

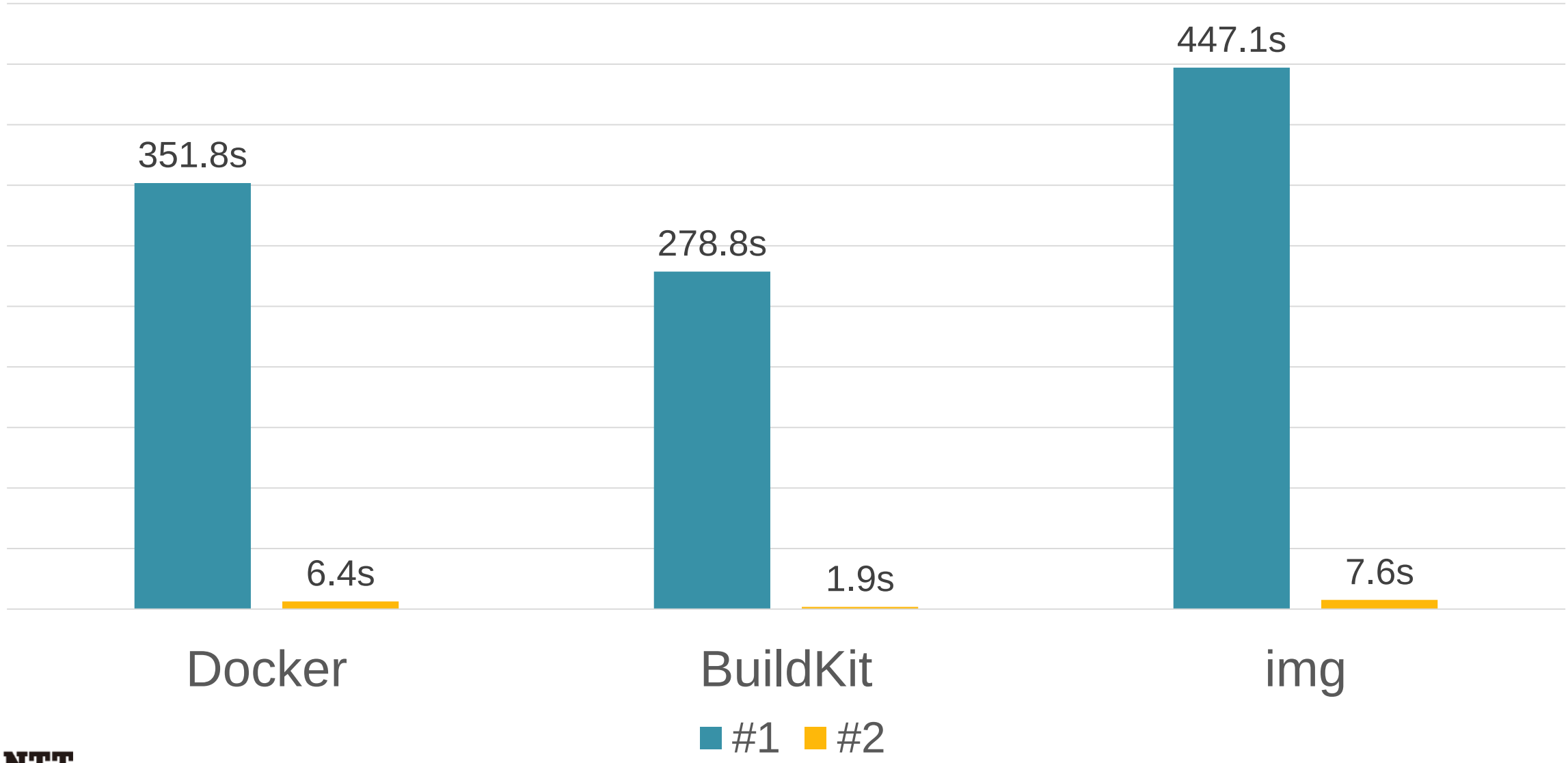


Another benchmark: moby/moby

- **Dockerfile used for the development of Moby**
- **Good example of complex DAG**
  - 13 stages can be executed in parallel at maximum
  - Buildah and Kaniko don't support this DAG at the moment
    - `` `FROM base` `` results in attempt to pull `` `docker.io/library/base` ``



Benchmark result: moby/moby

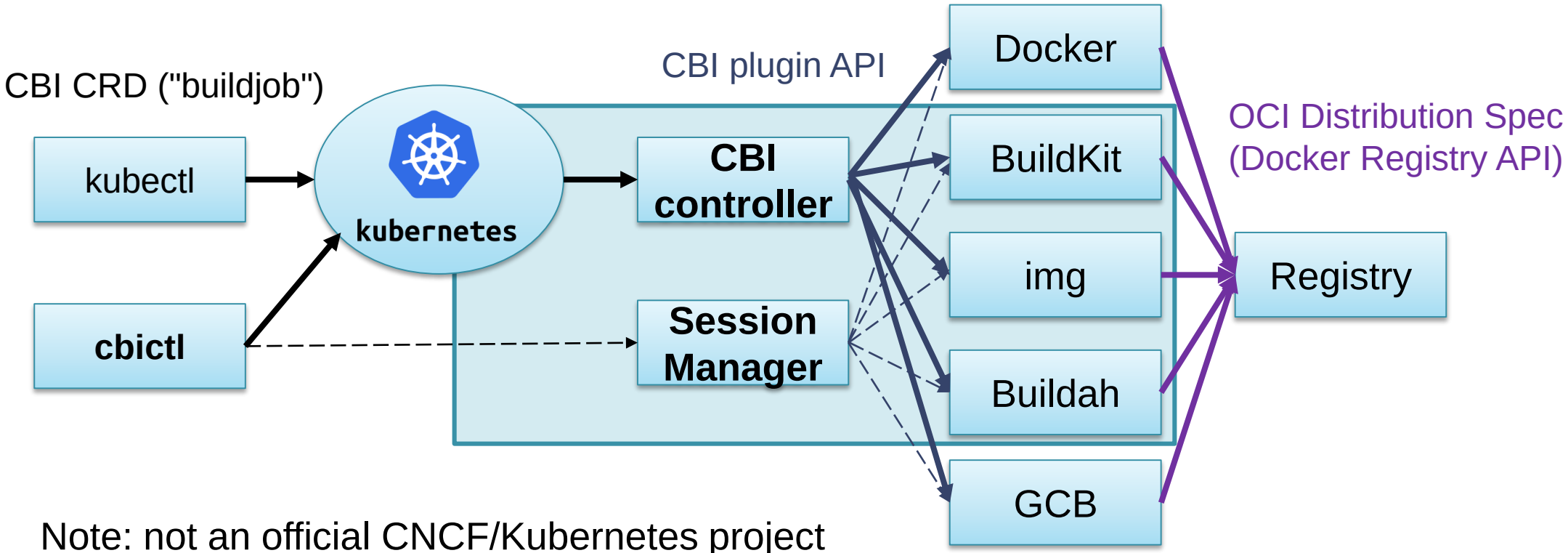


So.. which one is the best?

- **My recommendation is BuildKit, but it is not the "silver bullet"**
  - disclosure: I'm a maintainer of BuildKit
- **Other tools are attractive as well**
  - Language-specific builders, e.g. S2I
  - SUID-less rootless mode, e.g. Orca and Kaniko
  - Enterprise support, e.g. Buildah
- **Can we define the common interface for all of them?**

CBI: Container Builder Interface for Kubernetes

- https://github.com/containerbuilding/cbi
- **Defines "BuildJob" as a Kubernetes CRD**
- **Supports several backends**



Note: not an official CNCF/Kubernetes project

CBI: Container Builder Interface for Kubernetes

```
apiVersion: cbi.containerbuilding.github.io/v1alpha1
kind: BuildJob
metadata:
  name: ex0
spec:
  registry:
    target: example.com/foo/bar
    push: true
  language:
    dockerfile: {}
  context:
    git:
      url: git://github.com/foo/bar
  pluginSelector: plugin.name=buildkit
```

The CBI controller converts "BuildJob" CRD objects into Kubernetes `batch/v1` Job objects

Most plugins accept Dockerfile,
but non-Dockerfile plugins are also supported.
e.g. Source-to-Image

CBI: Container Builder Interface for Kubernetes


```
apiVersion: cbi.containerbuilding.github.io/v1alpha1
kind: BuildJob
metadata:
  name: ex0
spec:
  registry:
    target: example.com/foo/bar
    push: true
  language:
    dockerfile: {}
  context:
    git:
      url: git://github.com/foo/bar
  pluginSelector: plugin.name=buildkit
```

Registry and Git credentials can be provided as Kubernetes secret objects

Also supports ConfigMap, HTTP, S3, SFTP, and even Dropbox.. (using Rclone)

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CBI: Container Builder Interface for Kubernetes

- **Supported plugins:**
  - Docker
  - BuildKit
  - img
  - Buildah
  - kaniko
  - OpenShift Source-to-Image
  - Google Cloud Container Builder
    - Managed service for `docker build`

- **New plugin can be also added easily as a Kubernetes service**

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CBI: Container Builder Interface for Kubernetes

- **POC for Skaffold integration is available (GoogleContainerTools/skaffold#596)**

```
apiVersion: skaffold/v1alpha2
kind: Config
build:
  artifacts:
  - imageName: example.com/foo/bar
deploy:
  kubectl:
    manifests:
      - k8s-pod.yaml
profiles:
  - name: cbi
    build:
      cbi: {}
```

Deploy a Kubernetes pod using the image

By default the local Docker is used, but can be easily switched to CBI (`skaffold dev –p cbi`)

Conclusion

- **My recommendation is BuildKit (disclosure: I'm a maintainer)**
  - Will be integrated to Docker 18.06 experimentally (planned to be released by the end of this month)
- **But other tools are promising as well**
- **Now is the time for standardization**
  - https://github.com/containerbuilding/cbi