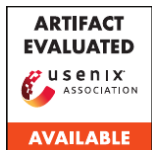


Practically Correct, Just-in-Time Shell Script Parallelization

OSDI 2022



binpa.sh  github.com/binpash/pash

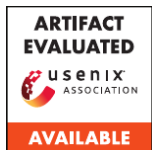


Practically Correct, Just-in-Time Shell Script Parallelization

OSDI 2022

or how to get from this:

```
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 0.0%  
[ ] 100.0%  
[ ] 0.0%
```



binpa.sh



github.com/binpash/pash

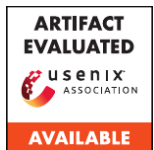
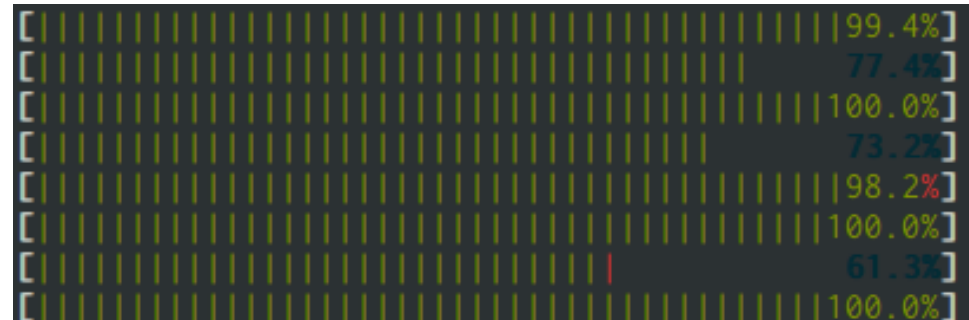


Practically Correct, Just-in-Time Shell Script Parallelization

OSDI 2022

or how to get from this:

to this:



binpa.sh



github.com/binpash/pash



Joint work with:



Tammam Mustafa



Jan Bielak



Dimitris Karnikis



Thurston Dang



Michael Greenberg



Nikos Vasilakis

Building on work by many others (in alphabetical order):



Achilles Benetopoulos



Lazar Cvetkovic



Shivam Handa



Kostas Mamouras



Radha Patel



Martin Rinard

shell

Used by everyone!

- Orchestration
 - Kubernetes deployment
 - Docker containers ...
- Data processing:
 - Downloading
 - Extracting
 - Preprocessing
 - Querying
- Automation Tasks
 - Configuration
 - Installation

Used by everyone!

- Orchestration
 - Kubernetes deployment
 - Docker containers ...
- Data processing:
 - Downloading
 - Extracting
 - Preprocessing
 - Querying
- Automation Tasks
 - Configuration
 - Installation

```
base="ftp://ftp.ncdc.noaa.gov/pub/data/noaa";
for y in {2015..2019}; do
  curl $base/$y | grep gz | tr -s" " | cut -d" " -f9 |
  sed "s;^;$base/$y/;" | xargs -n 1 curl -s | gunzip |
  cut -c 89-92 | grep -iv 999 | sort -rn | head -n 1 |
  sed "s/^/Maximum temperature for $y is: /"
done
```

Used by everyone!

- Orchestration
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```
base="ftp://ftp.ncdc.noaa.gov/pub/data/noaa";  
for y in {2015..2019}; do  
  curl $base/$y | grep gz | tr -s" " | cut -d" " -f9 |  
  sed "s;^;$base/$y/;" | xargs -n 1 curl -s | gunzip |  
  cut -c 89-92 | grep -iv 999 | sort -rn | head -n 1 |  
  sed "s/^/Maximum temperature for $y is: /"  
done
```

```
echo "Building parser..."  
eval $(opam config env)  
cd compiler/parser  
echo "|-- installing opam dependencies..."  
make opam-dependencies  
echo "|-- making libdash..."  
make libdash  
echo "|-- making parser..."  
make  
cd ../../..  
echo "Building runtime..."  
cd runtime/ ; make ; cd ../
```


Used by everyone

- Orchestration
 - Kubernetes deployment
 - Docker containers ...
- Data processing:
 - Downloading
 - Extracting
 - Preprocessing
 - Querying
- Automation Tasks
 - Configuration
 - Installation

```
# Check all possible clusters, as your .KUBECONFIG may have multiple contexts:
kubectl config view -o jsonpath='{.clusters[*]}.name{"\n"}{.cluster.server}{"\n"}{end}'
# Select name of cluster you want to interact with from above output:
export CLUSTER_NAME="some_server_name"
# Point to the API server referring the cluster name
APISERVER=$(kubectl config view -o jsonpath="{.clusters[?(@.name==\"$CLUSTER_NAME\")].cluster.server}")
# Gets the token value
TOKEN=$(kubectl get secrets -o jsonpath="{.items[?(@.metadata.annotations['kubernetes.io/service-account.name'] == 'default')].data.token}" | base64 --decode)
# Explore the API with TOKEN
curl -X GET $APISERVER/api --header "Authorization: Bearer $TOKEN" --insecure
base="ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/mon"
for y in {2015..2019}; do
  curl $base/$y | grep gz | tr -s "\n" " "
  sed "s;^;$base/$y/;" | xargs -n 1 curl
  cut -c 89-92 | grep -iv 999 | sort -rn | head -n 1
  sed "s/^/Maximum temperature for $y is: /"
done
echo "Building runtime..."
cd runtime/ ; make ; cd ../
```

Used by

```
#!/usr/bin/env sh
# Check
# kube
# Check
# TODO: Maybe first check if the repo is accessible via git?
# will install dependencies locally.
PLATFORM=$(uname | tr '[:upper:]' '[:lower:]')
URL='http://get.pash.ndr.md/'
VERSION='latest'
DOWNLOADER='curl'
alias curl='curl -s'
```

```
download () {
  command -v curl >/dev/null 2>&1 || { DOWNLOADER='wget'; alias curl='wget -qO-'
}; }
cmd_exists () {
  command -v $1 >/dev/null 2>&1 && echo 'true' || echo 'false';
}
```

```
Auton
Com
Insta
if [ $PLATFORM = 'darwin' ]; then
  echo 'PaSh is not yet well supported on OS X'
fi
INSTALL=0
while getopts 'i' opt; do
  case $opt in
    i) INSTALL=1 ;;
    *) echo 'Error in command line parsing' >&2
       exit 1
  esac
esac
pash-old-{$RANDOM}
nts=1 -C .
ot
```

```
IG may have multiple contexts:
ers[*]]{.name}{"\t"}{.cluster.server}{"\n"}{end}'
" above output:
```

```
name=="$CLUSTER_NAME\").cluster.server}")
tations['kubernetes.io/service-
```

```
ecure
r/parse
installing c,
dependencies
aking libdash..."
king parser..."
; runtime..."
make ; cd ../
```

Used

```
#!/usr/bin/...
# TODO
# w
P

lead -r -a flags "${microbenchmark_configs[@]}"; do
echo "Executing test: $microbenchmark"
# Execute the sequential script on the first run only
exec_seq="-s"
for n_in in "${n_inputs[@]}"; do
echo "Number of inputs: ${n_in}"
## Generate the intermediary script
python3 generate_microbenchmark_intermediary_scripts.py \
    $microbenchmarks_dir $microbenchmark $n_in $intermediary_dir "test"
for flag in "${flags[@]:1}"; do
echo "Flag: ${flag}"
## Execute the intermediary script
./execute_evaluation_script "${microbenchmark}" "${n_in}" "test_results" "test_" > /dev/null 2>&1
rm -f /tmp/eager*
## Only run the sequential the first time around
exec_seq=""
done
done
done
}

execute_tests "" "${script_microbenchmarks[@]}"
execute_tests "-c" "${pipeline_microbenchmarks[@]}"
echo "Below follow the identical outputs:"
grep --files-with-match "are identical" ../evaluation/results/test_results

echo "Below follow the non-identical outputs:"
grep -L "are identical" ../evaluation/results/test_results

TOTAL_TESTS=$(ls -la ../evaluation/results/ | wc -l)
PASSED_TESTS=$(grep --files-with-match "are identical" ../evaluation/results/test_results | wc -l)
echo "Summary: ${PASSED_TESTS}/${TOTAL_TESTS} tests passed"
```

id}'

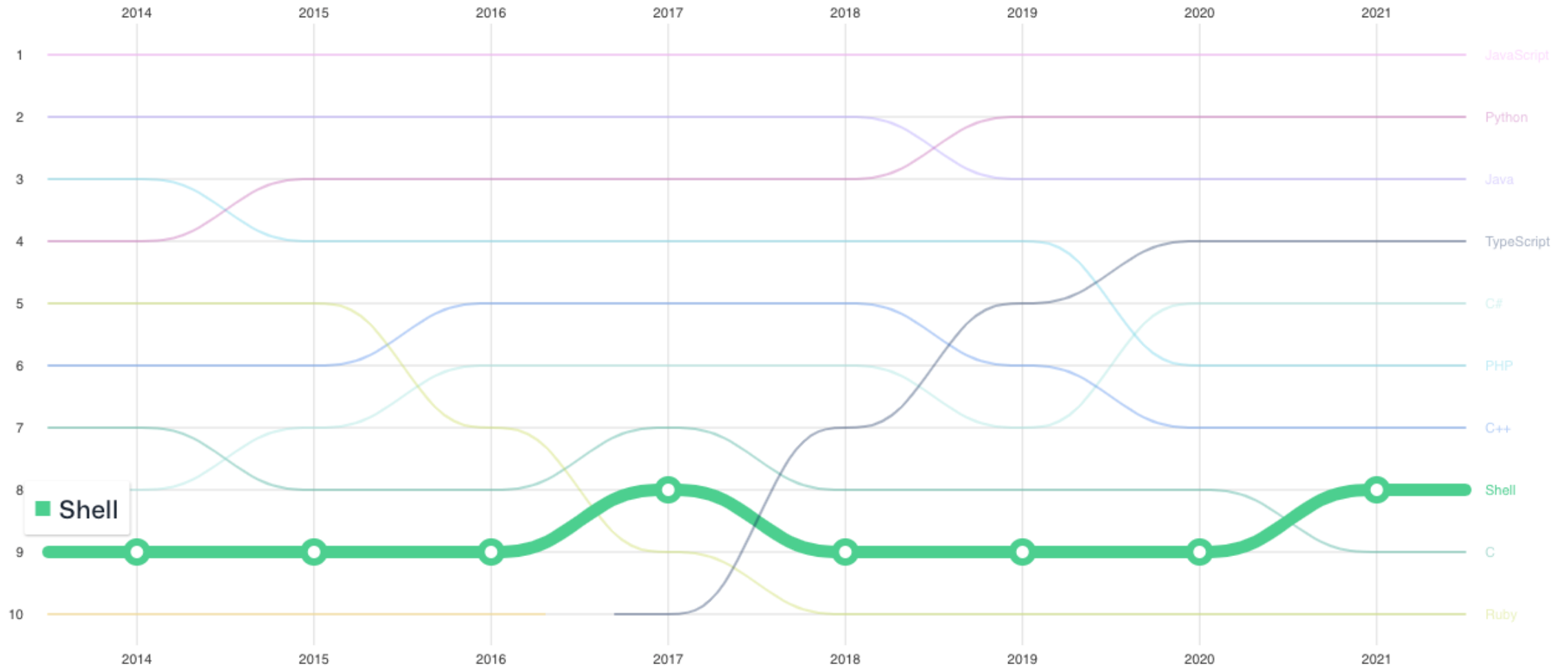
ver}')

.."

.."

..|

... for real



from the 2021 state of the octoverse: <https://octoverse.github.com>

Why? ... well, the shell is great

- Universal Composition
 - Composing arbitrary commands using files and pipes
 - Allows users to create powerful but succinct scripts
- Unix native
 - It is well suited to the Unix abstractions (files, strings, etc)
 - Offers great control and management of the file system
- Interactive
 - The complete system environment is accessible
 - Short commands and flags allows for quick experimentation

An example: Temperature Analysis

- This script computes the max temp in the US for the years 2015-2019

- To do so it:

- Preprocessing
- Fetches the indexes of temperature data archives
 - Downloads the archived temp data
 - Extracts the raw data

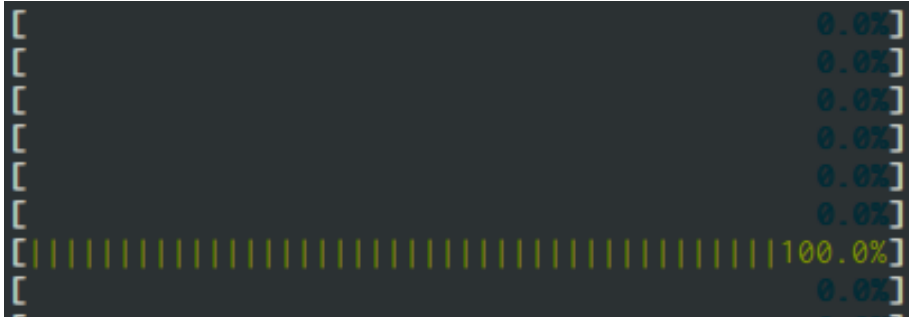
- Processing
- Cleans it
 - Computes the maximum

```
base="ftp://ftp.ncdc.noaa.gov/pub/data/noaa";
for y in {2015..2019}; do
  curl $base/$y | grep gz | tr -s" " | cut -d" " -f9 |
  sed "s;^;$base/$y/;" | xargs -n 1 curl -s | gunzip |
  cut -c 89-92 | grep -iv 999 | sort -rn | head -n 1 |
  sed "s/^/Maximum temperature for $y is: /"
done
```

- The preprocessing part is taken from the Hadoop book
 - Until the gunzip
- The final two lines replace the MapReduce program from Hadoop book
 - The MapReduce equivalent in Java is 150 lines of code :')

The shell is great but ...

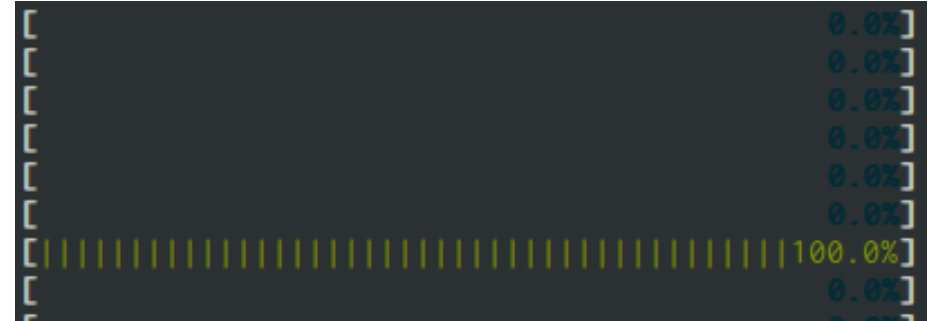
Shell scripts are mostly sequential!*



*Actually they have a ton more issues but we will come to that in the end

The shell is great but ...

Shell scripts are mostly sequential!*



Parallelizing requires a lot of manual effort:

- Using specific command flags (e.g., `sort -p`, `make -jN`)
- Using parallelization tools (e.g., GNU parallel)
- Rewriting script in parallel languages (e.g. Erlang)

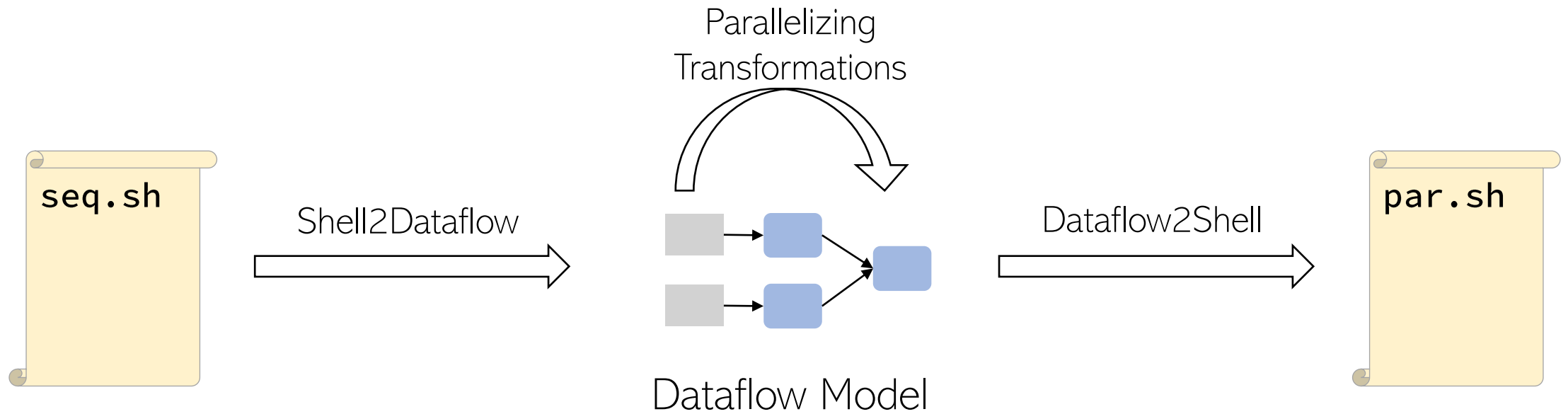


What did we do to deserve this??? :(

*Actually they have a ton more issues but we will come to that in the end

PaSh

PaSh



No tight coupling: Could work on top of any shell!

PaSh on Temperature Analysis

82GB (5y weather data)

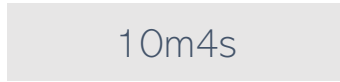
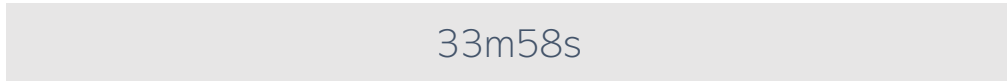
Preprocessing

Processing

bash

33m58s

10m4s



PaSh on Temperature Analysis

82GB (5y weather data)

Hadoop only focuses on this part

Preprocessing

Processing

bash

33m58s

10m4s

pash -w 16

16m39s

49s

2.04x

speedup for
preprocessing

12.31x

speedup for
processing

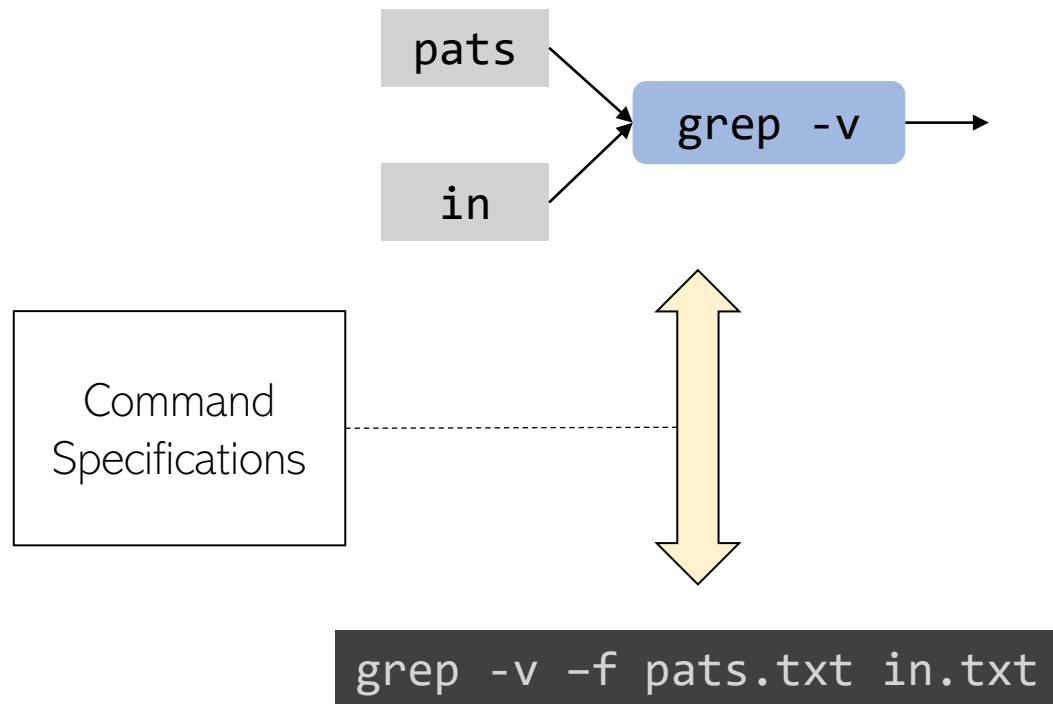
2.52x

combined speedup
for the full program

This part is not the focus of traditional parallelization frameworks but parallelizing it has the biggest impact

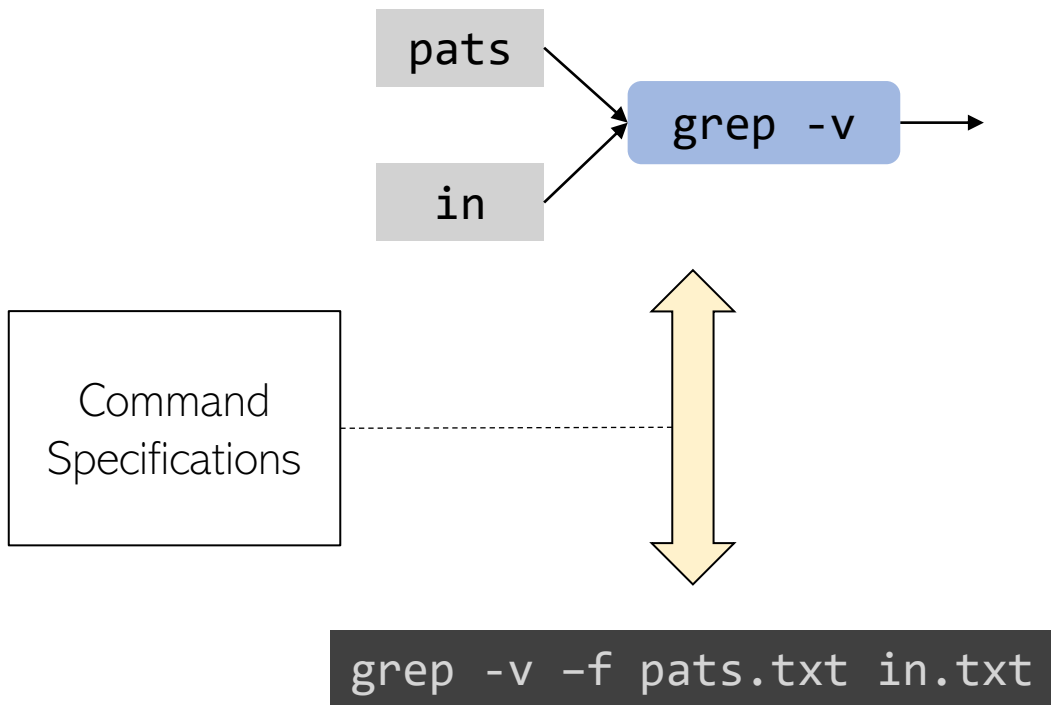
PaSh Insights

Command Specification Framework



PaSh Insights

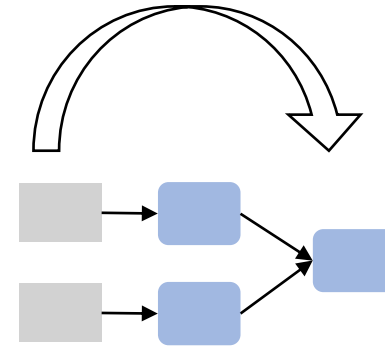
Command Specification Framework



Formalized 

Order Aware Dataflow Model

Parallelizing Transformations



 Transformations proven correct 

Read the PaSh papers at EuroSys 21 and ICFP 21 for more!

PaSh -- The static way



That should be OK, right?

That should be OK, right?



Conservative or unsound – Choose one

- The shell is dynamic:
 - Current directory
 - Environment variables
 - Unexpanded strings
 - File system

```
IN=${IN:-$TOP/pg}
mkdir $IN
cd $IN
echo 'Downloading, be patient...'
wget $SOURCE/data/pg.tar.xz
if [ $? -ne 0 ]; then
    echo "Download failed!"
    exit 1
fi
cat pg.tar.xz | tar -xJ

cd $TOP
OUT=${OUT:-$TOP/output}
mkdir -p "$OUT"
for input in $(ls ${IN}); do
    cat "$IN/$input" |
        tr -sc '[A-Z][a-z]' '[\012*]' |
        sort > "${OUT}/${input}.out"
done
```

Conservative or unsound – Choose one

- The shell is dynamic:
 - Current directory
 - Environment variables
 - Unexpanded strings
 - File system
- Static parallelization has to choose:
 - Sound but **conservative**
 - **Unsound** and optimistic

```
IN=${IN:-$TOP/pg}
mkdir $IN
cd $IN
echo 'Downloading, be patient...'
wget $SOURCE/data/pg.tar.xz
if [ $? -ne 0 ]; then
    echo "Download failed!"
    exit 1
fi
cat pg.tar.xz | tar -xJ

cd $TOP
OUT=${OUT:-$TOP/output}
mkdir -p "$OUT"
for input in $(ls ${IN}); do
    cat "$IN/$input" |
    tr -sc '[A-Z][a-z]' '[\012*]' |
    sort > "${OUT}/${input}.out"
done
```

PaSh-JIT

Just in time parallelization

- PaSh-JIT tries to parallelize as-late-as-possible™
- Provides critical information to the compiler:
 - State of shell, Variables, Directory, Files
- Not only correct, but also **faster!!!**
- How?
 - By constantly switching between evaluation and parallelization

Just in time parallelization

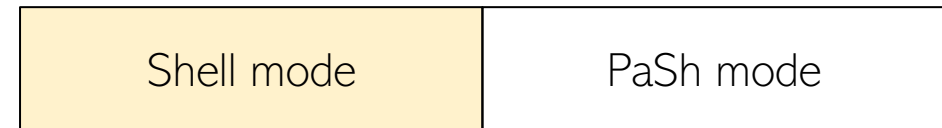
```
OUT=${OUT:-$TOP/out}
for input in $(ls ${IN}); do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

TOP=/pash
IN=/pash/in

Just in time parallelization

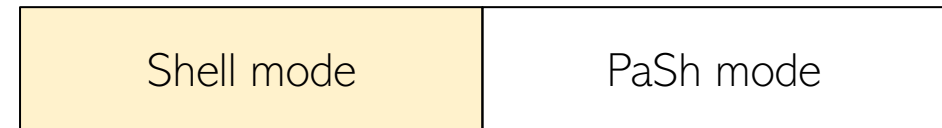
```
OUT=${OUT:-$TOP/out}
for input in $(ls ${IN}); do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```



TOP=/pash
IN=/pash/in

Just in time parallelization

```
OUT=/pash/out
for input in $(ls ${IN}); do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```



```
TOP=/pash
IN=/pash/in
```


Just in time parallelization

```
OUT=/pash/out
for input in $(ls ${IN}); do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
```

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
```

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
    cat "$IN/$input" |
    tr -sc '[A-Z][a-z]' '[\012*]' |
    sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
    cat "$IN/$input" |
    tr -sc '[A-Z][a-z]' '[\012*]' |
    sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Expanding

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
  cat "$IN/$input" |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > "${OUT}/${input}.out"
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
  cat /pash/in/in1 |
  tr -sc '[A-Z][a-z]' '[\012*]' |
  sort > /pash/out/in1.out
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
    cat /pash/in/in1 |
    tr -sc '[A-Z][a-z]' '[\012*]' |
    sort > /pash/out/in1.out
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Parallelize?

Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
    mkfifo f1 f2 f3 f4
    cat /pash/in/in1 | split f1 f2 &
    ... &
    sort < f1 > f3 &
    sort < f3 > f4 &
    sort -m f3 f4 > /pash/out/in1.out
    rm f1 f2 f3 f4
done
```

Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

Parallelize?
Success!

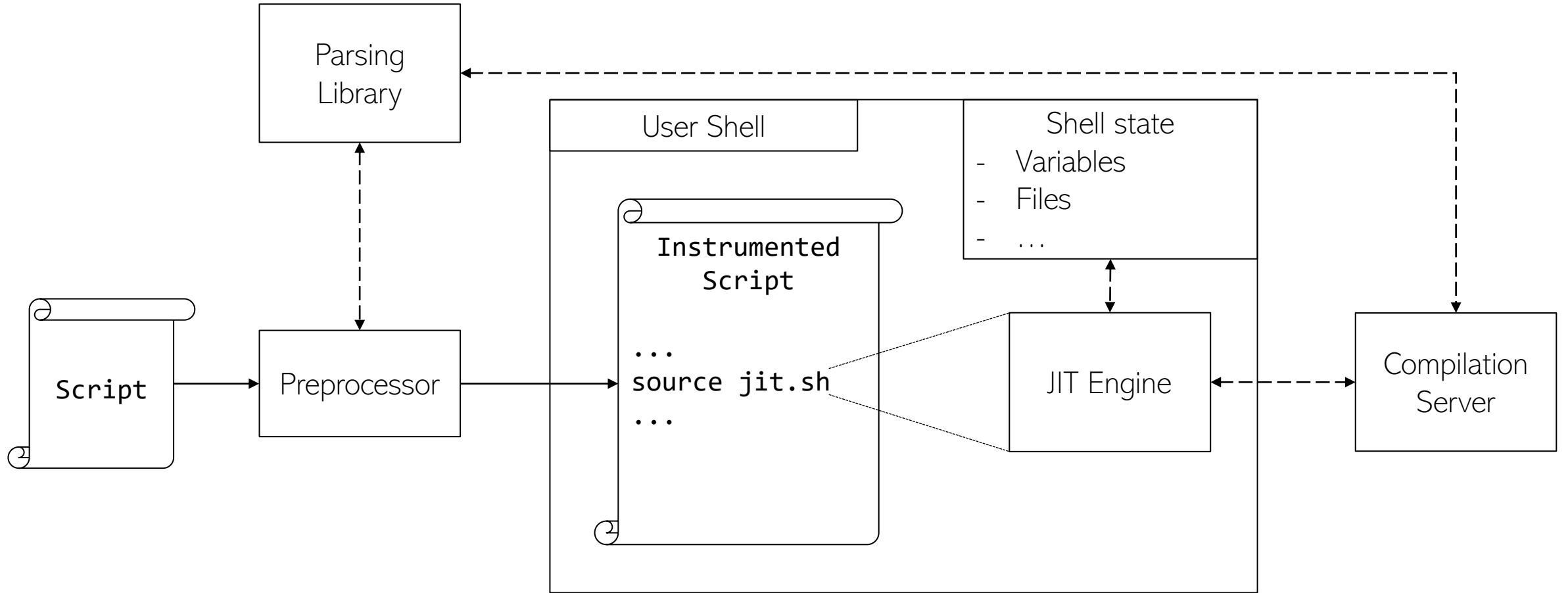
Just in time parallelization

```
OUT=/pash/out
for input in in1 in2; do
    mkfifo f1 f2 f3 f4
    cat /pash/in/in1 | split f1 f2 &
    ... &
    sort < f1 > f3 &
    sort < f3 > f4 &
    sort -m f3 f4 > /pash/out/in1.out
    rm f1 f2 f3 f4
done
```

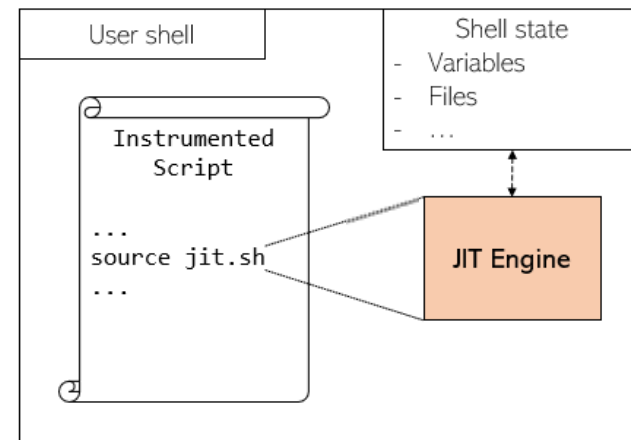
Shell mode	PaSh mode
------------	-----------

```
TOP=/pash
IN=/pash/in
OUT=/pash/out
input=in1
```

PaSh-JIT overview

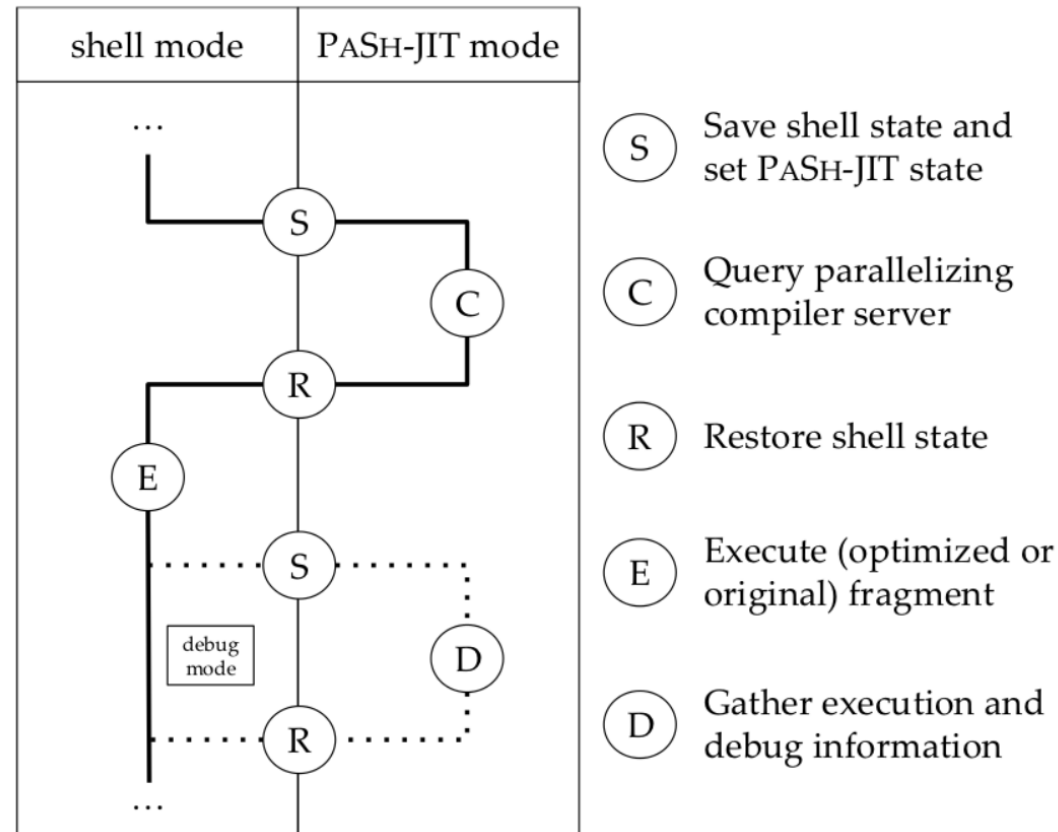
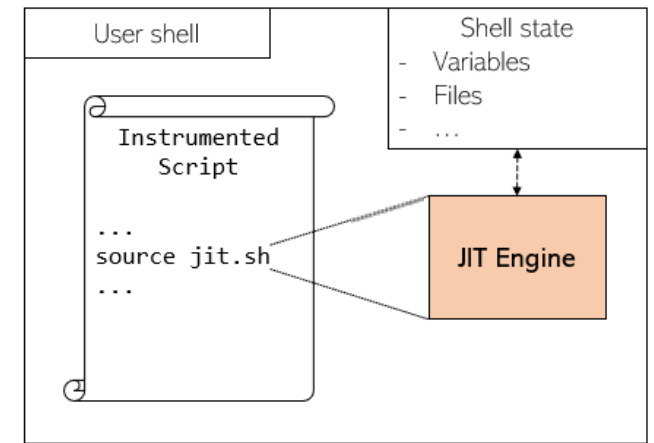


JIT Engine

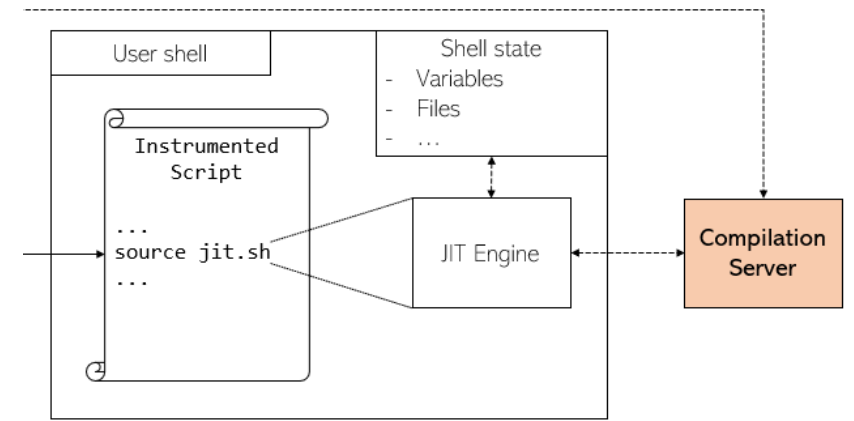


JIT Engine

Hides compilation from the perspective of the shell



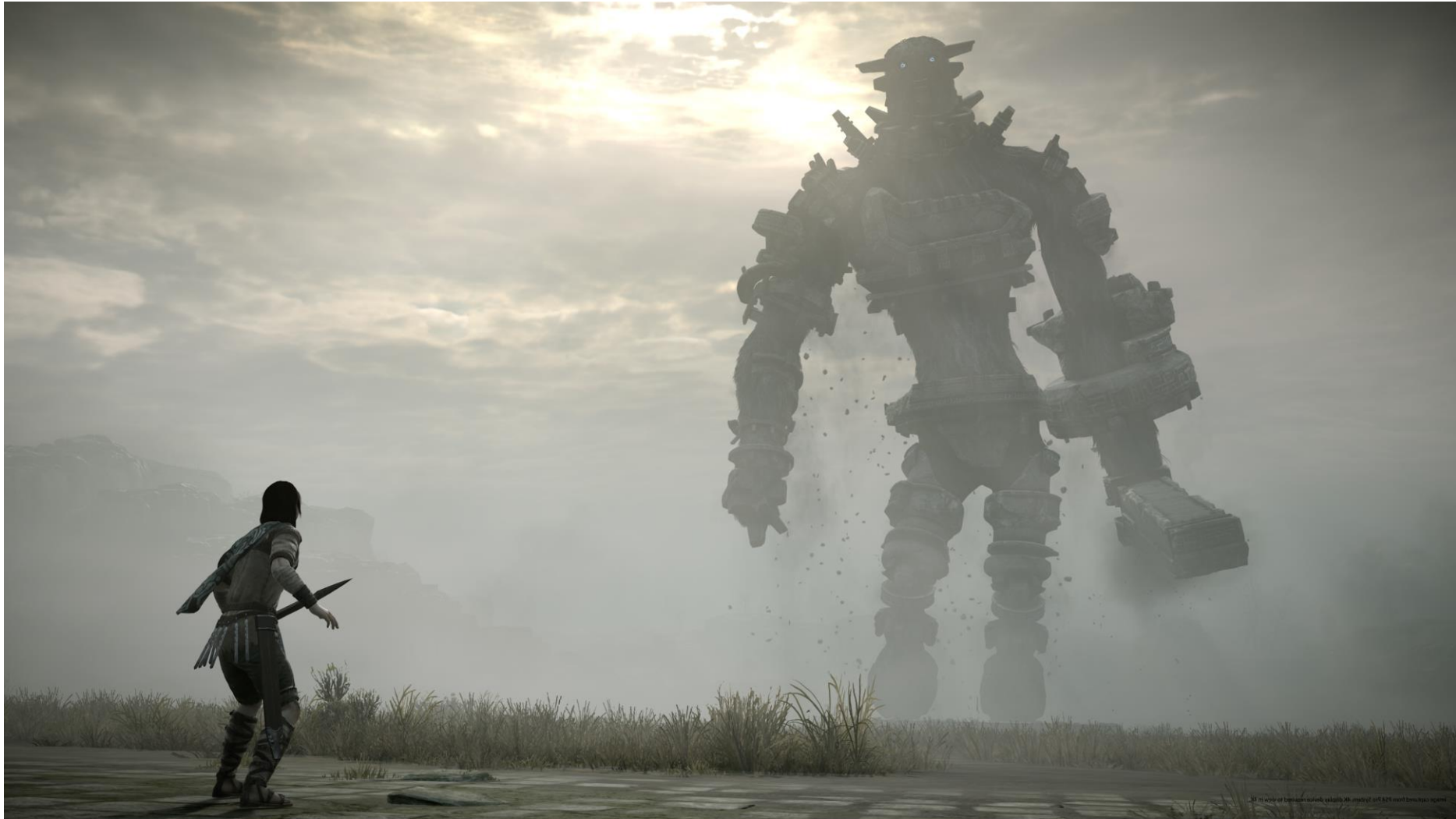
Compilation Server



- The compilation server reduces latency!
 - Doesn't require initializations and keeps state in memory
 - Necessary for feasibility in practice (in tight loops every ms counts)
- Also enables additional optimizations
 - Parallelization of independent fragments (e.g., iterations that touch different files)
 - Profile-guided optimizations (e.g., configuring parallelization width)
- For more, check out our paper

Evaluation

Evaluation: Correctness



Evaluation: Correctness

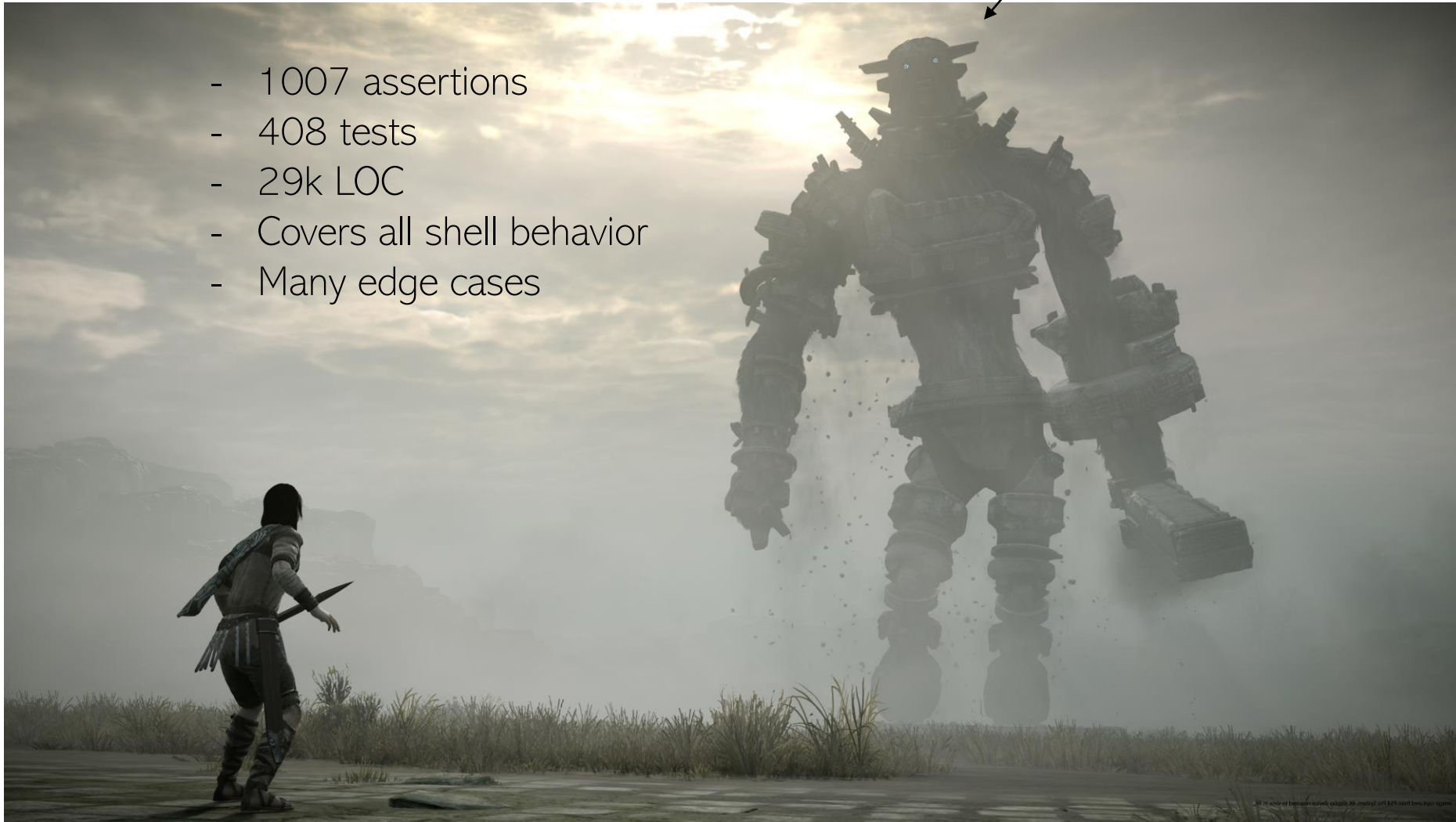
POSIX Shell Test Suite



Evaluation: Correctness

POSIX Shell Test Suite

- 1007 assertions
- 408 tests
- 29k LOC
- Covers all shell behavior
- Many edge cases



Evaluation: POSIX test suite

- Out of the 408 tests
 - Bash passes 376 and fails 32 tests
 - PaSh-JIT passes 374 and fails 34 tests
- Divergence in these two tests is only in the exit status
 - Both return with an error, though different code

Evaluation: POSIX test suite

- Out of the 408 tests
 - Bash passes 376 and fails 32 tests
 - PaSh-JIT passes 374 and fails 34 tests
- Divergence in these two tests is only in the exit status
 - Both return with an error, though different code
- Other shells compared to bash:

	Both Bash and X fail	Bash succeeds X fails
dash	1	20
ksh	2	22
mksh	1	29
posh	4	52
yash	1	20

Evaluation: POSIX test suite

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- Other shells compared to bash:
- Various shell failures on POSIX tests:

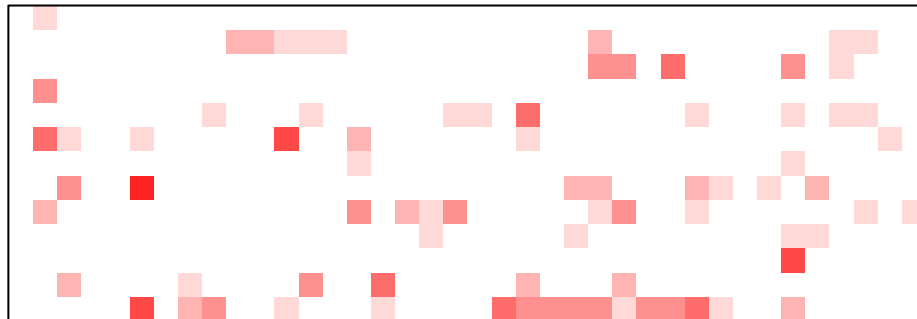


	Both Bash and X fail	Bash succeeds X fails
dash	1	20
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posh	4	52
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Evaluation: POSIX test suite

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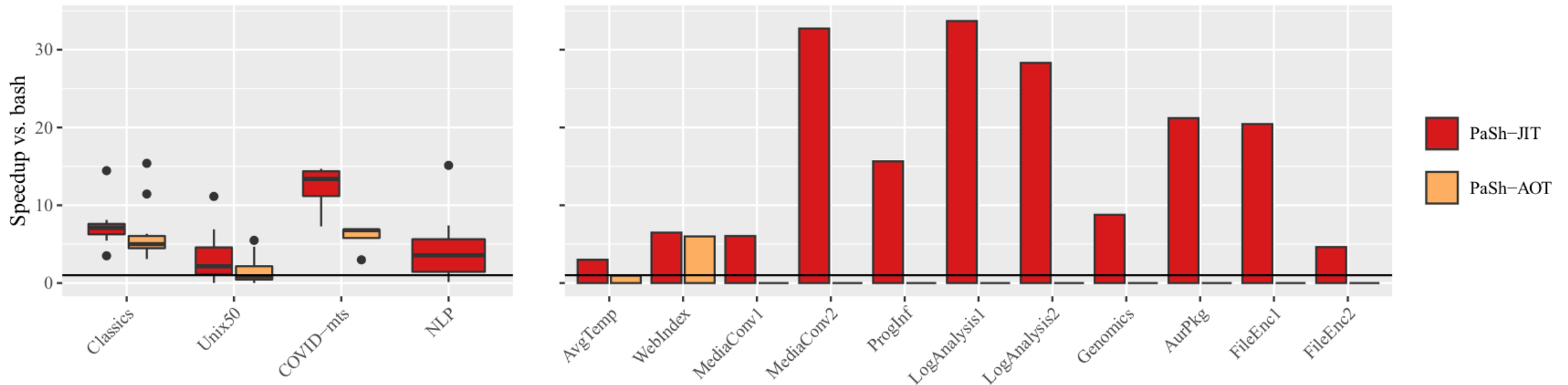
By following a lightweight shim approach (instead of reimplementing) we achieve very high compatibility with bash ✨



	Both Bash and X fail	Bash succeeds X fails
dash	1	20
ksh	2	22
mksh	1	29
posh	4	52
yash	1	20

Evaluation: Performance

- Evaluating on 82 shell scripts (4 suites and 11 standalone scripts)



Avg speedups: PaSh-JIT (x5.8) – PaSh-AOT (x2.9)

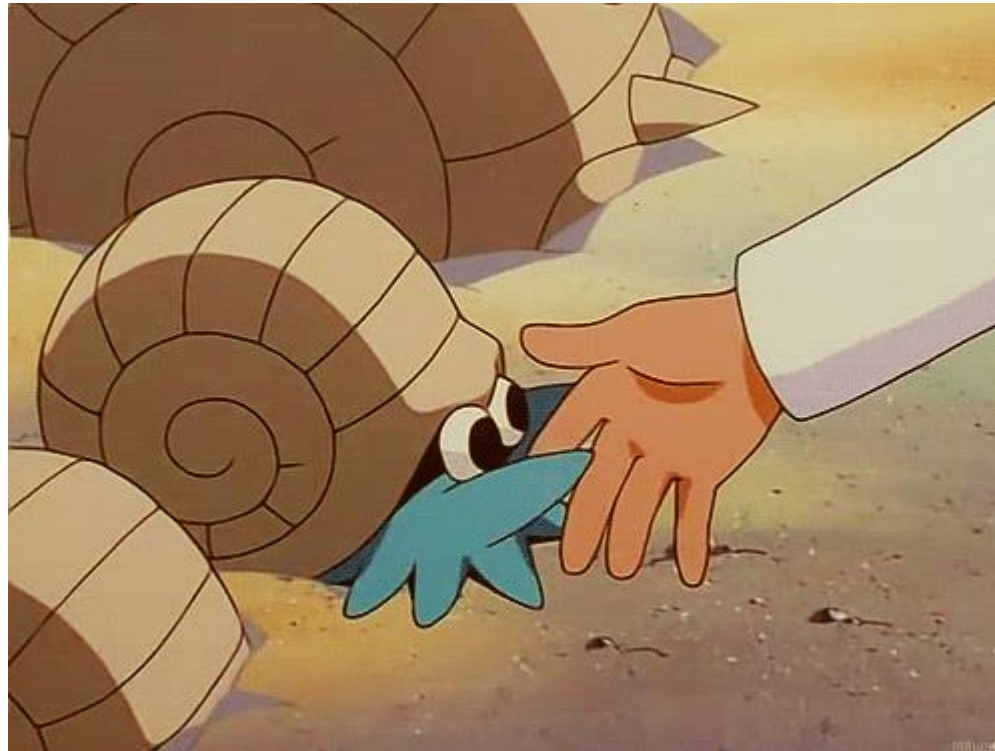
Conclusion

Conclusion

- Shells were angry that we tried to parallelize statically

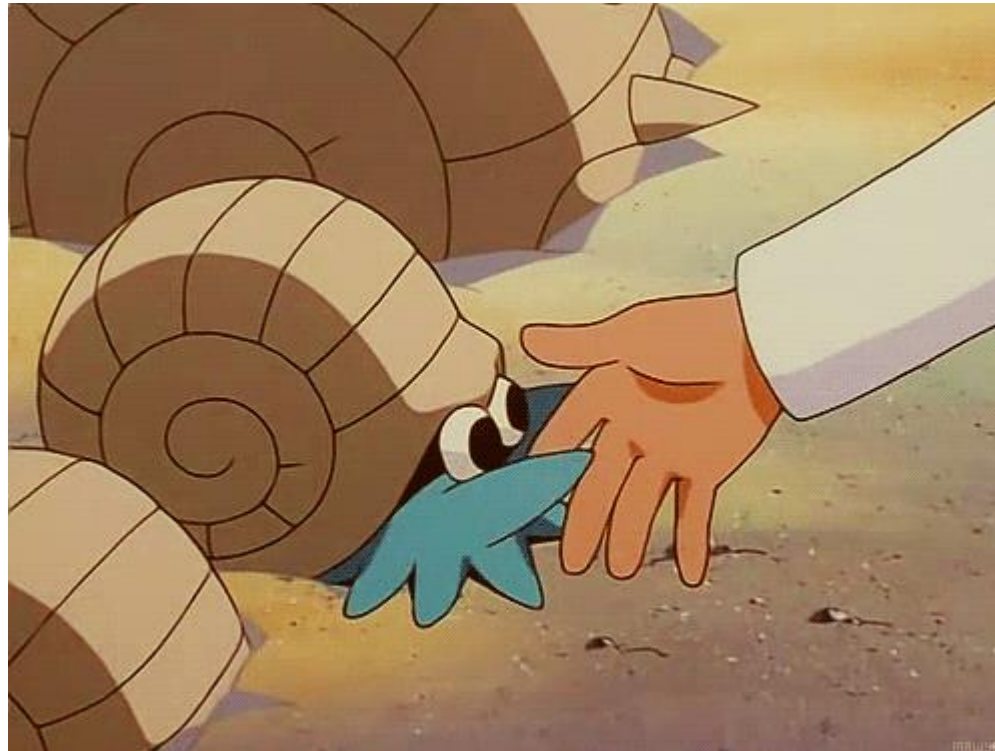
Conclusion

- Shells were angry that we tried to parallelize statically
- We can make them happy by being dynamic




Conclusion

- Shells were angry that we tried to parallelize statically
- We can make them happy by being dynamic
- Correct
- And fast!



The shell has more problems...

- Error-proneness
 - accidentally ``rm -rf /`` 
- Hard to learn
 - still googling for if-then-else shell syntax
- Redundant recomputation
- Lack of support for contemporary deployments
 - managing a distributed cluster

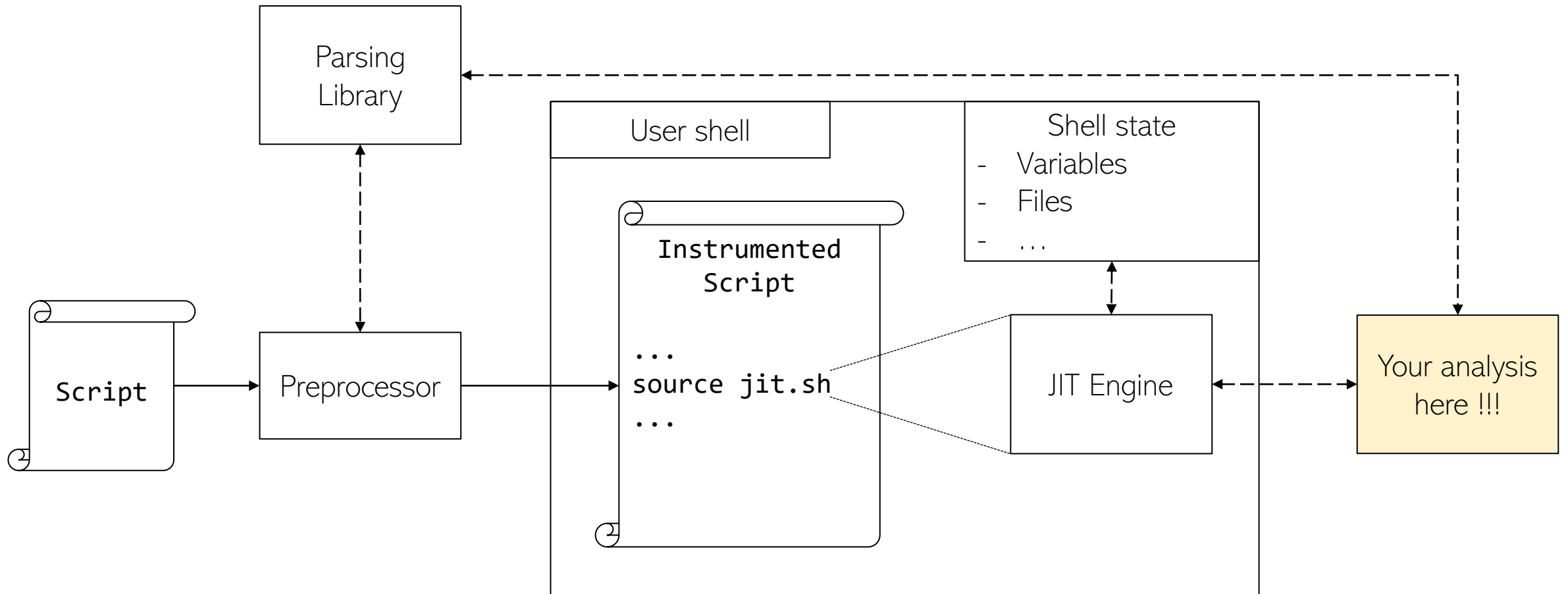
Recent exceptions: Rattle [1] and Riker [2]

[1] Sarah Spall, Neil Mitchell, and Sam Tobin-Hochstadt. “Build scripts with Perfect Dependencies.” OOPSLA. 2020.


[2] Charlie Curtsinger, and Daniel W. Barowy. “Riker: Always-Correct and Fast Incremental Builds from Simple Specifications” ATC. 2022.

The JIT part of PaSh-JIT is an enabler

- The JIT structure of PaSh-JIT enables additional analyses/solutions

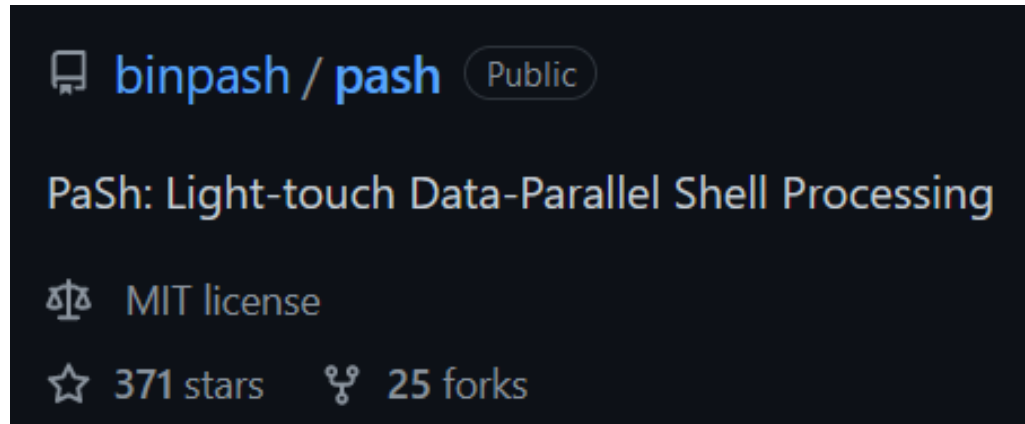


Some exciting future directions

- A shell monitor that ensures that safety/security props are not violated
- A fully distributed shell 
- An incremental execution shell
- Talk to us if you have ideas!
- Michael and Nikos are hiring!

Practical impact and availability

- PaSh is open source and hosted by the Linux Foundation



- It is virtually indistinguishable from bash (406/408 POSIX tests)
 - And requires no modifications/reimplementation

- OSDI artifact badges



- Download it and play binpa.sh  github.com/binpash/pash