Ready, set, Go!

Data-race detection and the Go language

Daniel S. Fava
`danielsf@ifi.uio.no`

Martin Steffen
`msteffen@ifi.uio.no`

Department of informatics
University of Oslo, Norway

SBMF'19
São Paulo, Brazil

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- Unknown semantics (under weak-memory)

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     T1                     |        T2
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done = true                 |   while (!done) {}
                            |   print("t2", z)
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Relaxed memory models are complex.

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Origin of the *happens-before* relation and *vector clocks.*

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Shared memory, but

no channels,

no synchronization via message passing.

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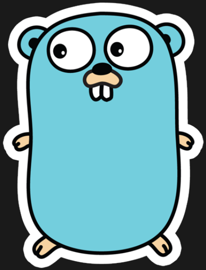

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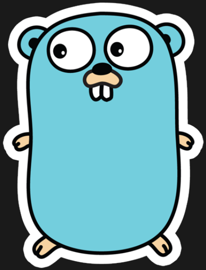

Operational Semantics of a Weak Memory Model with Channel Synchronization

Daniel Fava   Martin Steffen   Volker Stolz

[FM'18, JLAMP'18]

II. Background

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Concurrent: not ordered by happens-before.

The Go memory model.

[Go memory model, 2014]
replacing *thread* by *goroutine*

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- *Within a single thread,*
  - *reads and writes must behave as if they executed in the order specified by the program;*
  - *reorder is allowed only when it does not change the behavior within that thread.*
- *The execution order observed by one thread may differ from the order observed by another.*

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Given a channel c with capacity k,
the i^{th} receive from c happens-before the $(i+k)^{th}$ send completes.

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III. Our approach

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Intuition

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Efficiency

An access to memory is captured by an event

$(m, ?z) \qquad (m', !z)$

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- Happened-before set, E_{hb}

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A memory cell keeps track of

- a variable's value
- set of events that have happened-before to the variable, E_{hb}

$p\langle E_{hb}, t\rangle$

$p\langle E_{hb}, t\rangle$ $\qquad$ $(\!|E^{z}_{hb},\ z{:=}v|\!)$

$$p\langle E_{hb}, t\rangle \parallel (\!| E^z_{hb},\ z{:=}v |\!)$$

$$p\langle E_{hb}, z := v'; t\rangle \parallel (\!| E^{z}_{hb},\ z{:=}v |\!)$$

$$
\begin{aligned}
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Sends and Receives transmit a thread's happens-before set

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Threads "learn" from each other about past events

Channel receive

$$\frac{v \neq \bot \qquad E'_{hb} = E_{hb} + E''_{hb}}{\begin{array}{rcll} c_b[q_1] \parallel & p\langle E_{hb}, \texttt{let}\ r = \leftarrow c\ \texttt{in}\ t\rangle & \parallel c_f[q_2 :: (v, E''_{hb})] & \rightarrow \\ c_b[E_{hb} :: q_1] \parallel & p\langle E'_{hb}, \texttt{let}\ r = v\ \texttt{in}\ t\rangle & \parallel c_f[q_2] & \end{array}}$$

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Channel send

$$\frac{\neg closed(c_f[q_2]) \qquad E'_{hb} = E_{hb} + E''_{hb}}{\begin{array}{r}c_b[q_1 :: E''_{hb}] \parallel \quad p\langle E_{hb}, c \leftarrow v; t\rangle \quad \parallel c_f[q_2] \quad \rightarrow \\ c_b[q_1] \parallel \qquad p\langle E'_{hb}, t\rangle \qquad \parallel c_f[(v, E_{hb}) :: q_2]\end{array}}$$

Efficiency


z_0

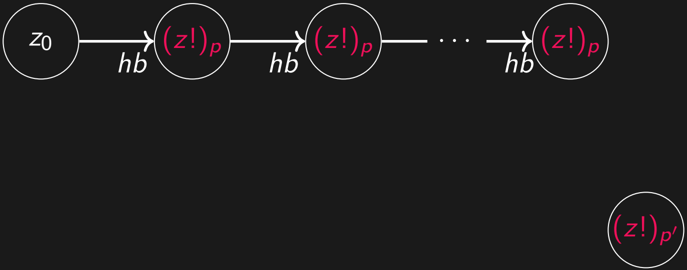
z_0 $(z!)_p$

$$z_0 \xrightarrow[hb]{} (z!)_p$$

$$z_0 \xrightarrow{hb} (z!)_p \qquad (z!)_p$$

$$z_0 \xrightarrow{hb} (z!)_p \xrightarrow{hb} (z!)_p$$

$$z_0 \xrightarrow[hb]{} (z!)_p \xrightarrow[hb]{} (z!)_p \longrightarrow \cdots \xrightarrow[hb]{} (z!)_p$$


z_0
hb
$(z!)_p$
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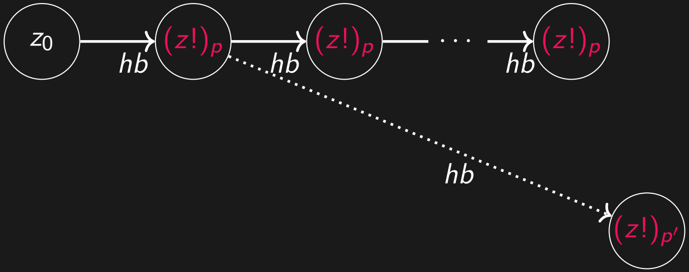
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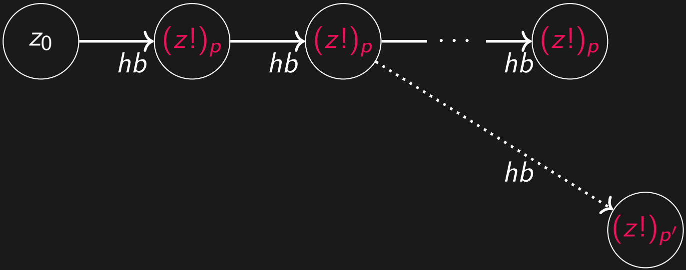
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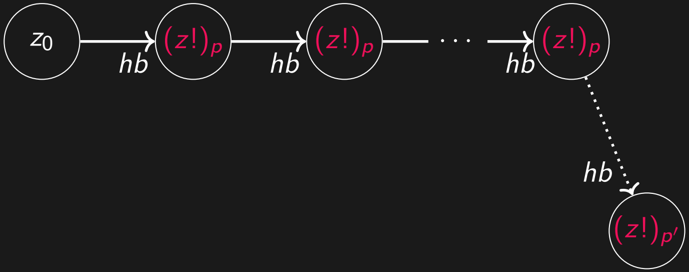
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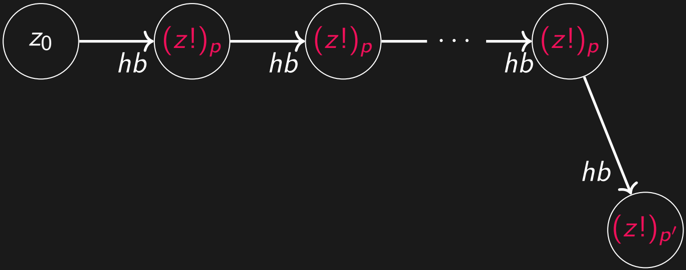
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$$\llparenthesis E^z_{hb},\ z{:=}v \rrparenthesis$$

$$\llparenthesis E_{hb}^{z},\ z{:=}v \rrparenthesis$$

$$(m, !z),\ (m', ?z) \in E_{hb}^{z}$$

$$(\!|E^z_{hb},\ z{:=}v|\!)$$

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Remember only the last write

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Remember only the last write

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$$(\!|E_{hb}^{z},\ z{:=}v|\!)$$

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Remember only the last write

$$m(\!|E_{hb}^{r},\ z{:=}v|\!)$$

$$E_{hb}^{z} \downarrow_{!}$$

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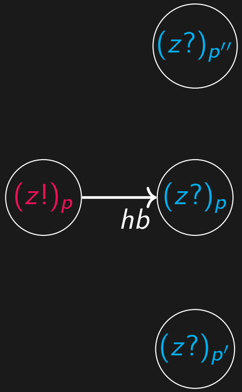
$(z!)_p$

$(z!)_p$ $(z?)_p$

$$(z!)_p \xrightarrow[hb]{} (z?)_p$$



$(z?)_{p''}$
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hb
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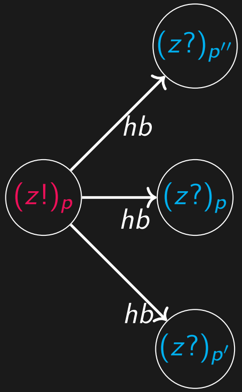
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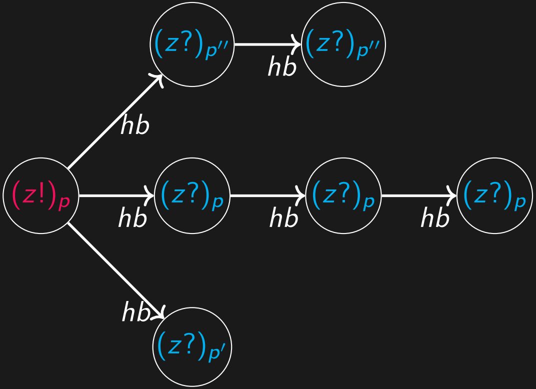
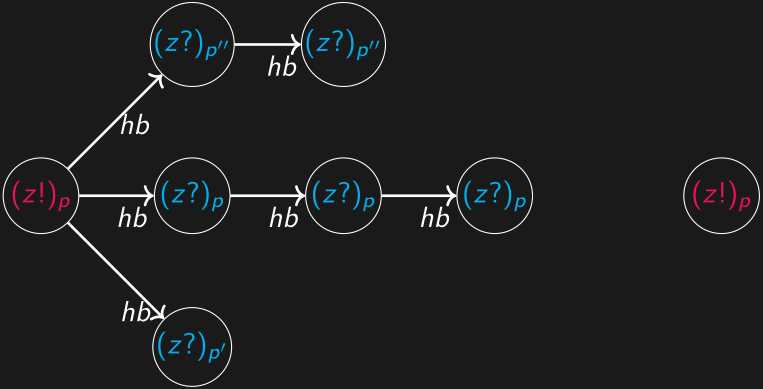
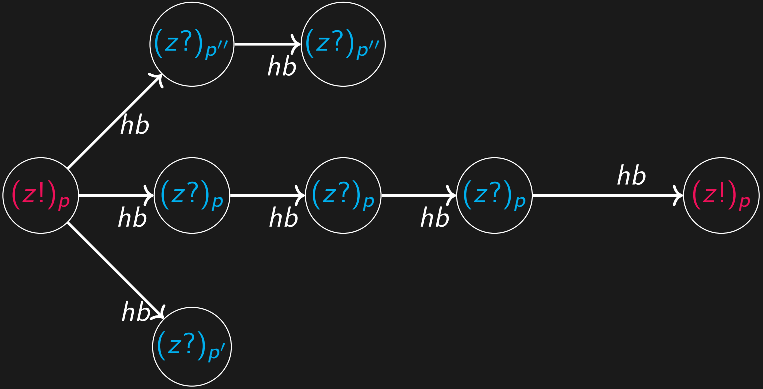
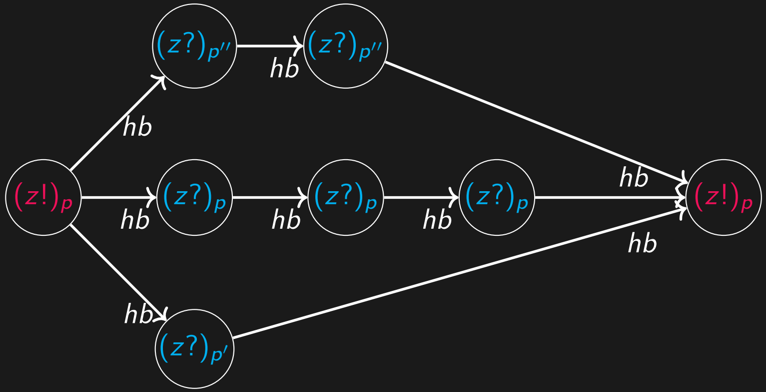
hb
$(z?)_{p'}$

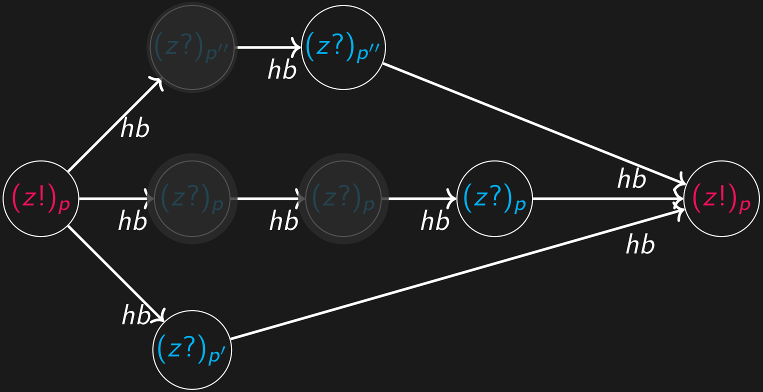

$(z!)_p$
$(z?)_{p''}$
$(z?)_{p''}$
$(z?)_p$
$(z?)_p$
$(z?)_p$
$(z?)_{p'}$
hb
hb
hb
hb
hb
hb


(z!)p
(z?)p''
(z?)p''
(z?)p
(z?)p
(z?)p
(z?)p'
(z!)p
hb
hb
hb
hb
hb
hb

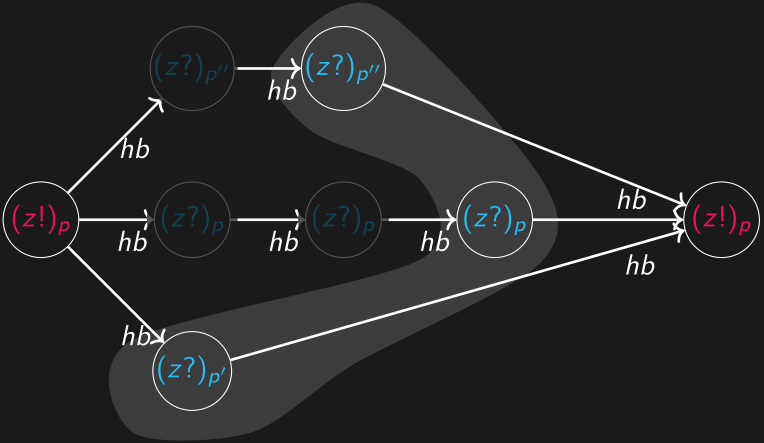

$(z?)_{p''}$
hb
$(z?)_{p''}$
hb
$(z!)_p$
hb
$(z?)_p$
hb
$(z?)_p$
hb
$(z?)_p$
hb
$(z!)_p$
hb
$(z?)_{p'}$



$(z!)_p$
$(z?)_{p''}$
$(z?)_{p''}$
$(z?)_p$
$(z?)_p$
$(z?)_p$
$(z?)_{p'}$
$(z!)_p$
hb



$(z!)_p$
$(z?)_{p''}$
$(z?)_{p''}$
$(z?)_p$
$(z?)_p$
$(z?)_p$
$(z?)_{p'}$
$(z!)_p$
hb



$(z!)_p$
$(z?)_{p''}$
$(z?)_{p''}$
$(z?)_p$
$(z?)_p$
$(z?)_p$
$(z?)_{p'}$
$(z!)_p$
hb

Updated *write*-rule for efficient race detection.

$$\frac{(m, !z) \in E_{hb} \qquad E^r_{hb} \subseteq E_{hb} \qquad \mathit{fresh}(m') \qquad E'_{hb} = \{(m', !z)\} \cup (E_{hb} - E_{hb} \downarrow_z)}{\begin{array}{ll} p\langle E_{hb}, z := v'; t\rangle & \parallel m(\!|E^r_{hb},\ z{:=}v|\!) \rightarrow \\ p\langle E'_{hb}, t\rangle & \parallel m'(\!|\emptyset,\ z{:=}v'|\!) \end{array}}$$

Updated *read*-rule for efficient race detection.

$$\frac{\begin{array}{l}(m, !z) \in E_{hb} \qquad \mathit{fresh}(m') \\ E'^{r}_{hb} = \{(m', ?z)\} \cup (E^{r}_{hb} - E_{hb}\downarrow_z) \\ E'_{hb} = \{(m', ?z)\} \cup (E_{hb} - E_{hb}\downarrow_z) \cup \{(m, !z)\}\end{array}}{\begin{array}{ll}p\langle E_{hb}, \mathtt{let}\ r = \mathtt{load}\ z\ \mathtt{in}\ t\rangle & \parallel m(\!|E^{r}_{hb}, z{:=}v|\!) \rightarrow \\ p\langle E'_{hb}, \mathtt{let}\ r = \ v\ \mathtt{in}\ t\rangle & \parallel m(\!|E'^{r}_{hb}, z{:=}v|\!)\end{array}}$$

Offline garbage-collection.

$$\frac{\begin{array}{rl} E'_{hb} = E_{hb} & - \{(\hat{m}, !z) \mid (\hat{m}, !z) \in E_{hb} \ \wedge \ \hat{m} \neq m\} \\ & - \{(\hat{m}, ?z) \mid (\hat{m}, ?z) \in E_{hb} \ \wedge \ (\hat{m}, ?z) \notin E^r_{hb}\} \end{array}}{p\langle E_{hb}, t\rangle \parallel m(\!|E^r_{hb},\ z{:=}v|\!) \to p\langle E'_{hb}, t\rangle \parallel m(\!|E^r_{hb},\ z{:=}v|\!)}$$

Vector clocks, Djit+ and FastTrack.

Think of a clock as natural number.
A *vector clock* maps a thread id to a clock.

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In Djit$^+$ and FastTrack, each thread u has a vector clock C_u,

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- its own time,
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$$C_u$$

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$$C_u(v)$$

Complexity analysis

Memory per thread	Djit$^+$ FastTrack	Our approach

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worst-case	$O(\tau)$	$O(\nu\tau)$

τ number of threads

ν number of variables

Complexity analysis

Memory per thread	Djit$^+$ FastTrack	Our approach
worst-case	$O(\tau)$	$O(\nu\tau)$
best-case	$O(1)$	

τ number of threads

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Complexity analysis

Memory per thread	Djit$^+$ FastTrack	Our approach
worst-case	$O(\tau)$	$O(\nu\tau)$
best-case	$O(1)$	$O(1)$

τ number of threads

ν number of variables

Comparison with TSan.

Also in the paper

Rules for

- synchronous communication
- dynamic channel and thread creation
- data-race reporting, etc

Connection with trace theory

Summary

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Data-race detection in terms of channel communication

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- message passing as synchronization primitive

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Data-race detection in terms of channel communication

- message passing as synchronization primitive
- no vector-clocks; based directly on happens-before relation
- most recent write, most recent reads, garbage collection
- models happens-before as described by the Go memory model

Future work

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- Implementation

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- Proof of "minimality of information"

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  Least amount of event information that must be kept

  Largest amount of information that can be garbage collected

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Questions?

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- Fava, D., Steffen, M., and Stolz, V. (2018a). Operational semantics of a weak memory model with channel synchronization.
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