Profile Guided Offline Optimization of Hidden Class Graphs for JavaScript VMs in Embedded Systems

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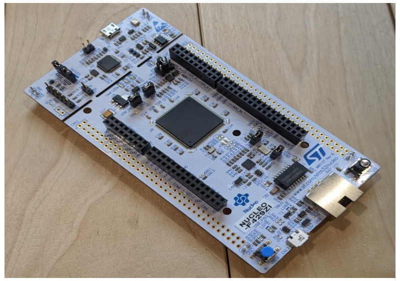
JavaScript in IoT

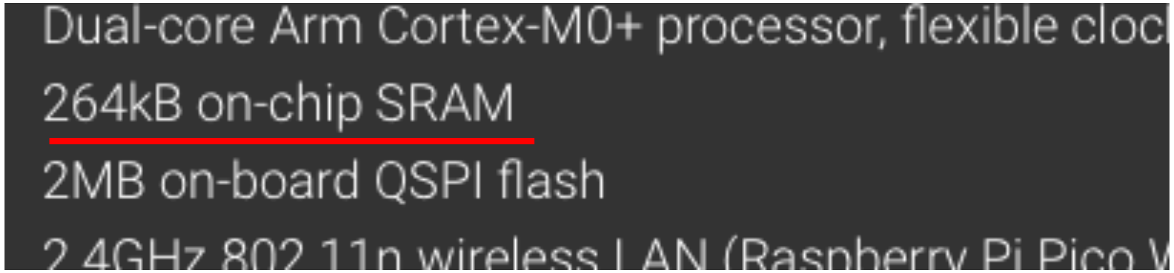
- JavaScript engines for IoT became popular
  - IoT.js, Moddable, eJSVM,…
- Challenge: memory footprint
  - Around 256 KB of RAM is available
  - More than 20 KB of RAM is occupied by meta-objects in eJSVM



STM32F429

- Arm Cortex-M4
- **256 KB of SRAM**

Raspberry Pi pico specification



Dual-core Arm Cortex-M0+ processor, flexible cloc

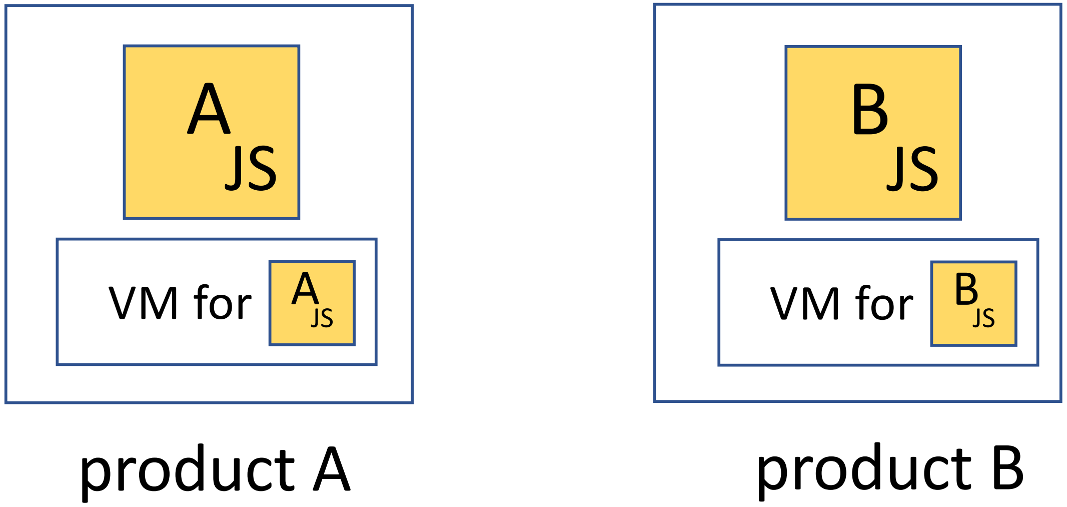
264kB on-chip SRAM

2MB on-board QSPI flash

2.4GHz 802.11n wireless LAN (Raspberry Pi Pico W

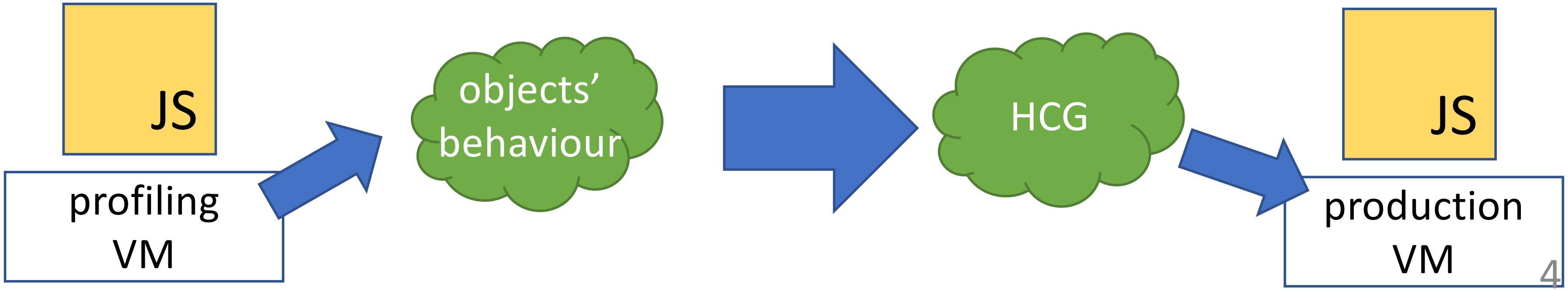
Closed World Assumption

- We can assume program is fixed for a particular IoT product
  - For product A, VM executes only A.js
- VM specialisation to a particular application is feasible



Overview of Our Work

- Specialise hidden class graph (HCG)
  - HCG represents type information of objects
  - HCG is created and grows during execution in accordance with program's behaviour
- Steps
  1. Collect objects' behaviour from profiling run
  2. Construct a static HCG and optimise it offline
  3. Use static HCG in actual runs



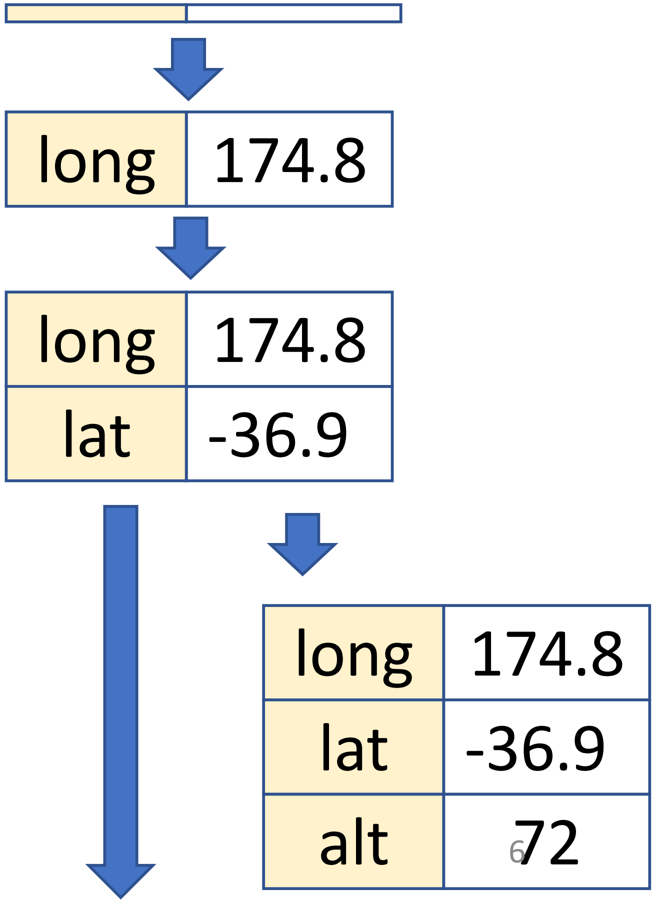
Agenda

- Introduction
- Hidden classes
- Optimised Hidden Class Construction
- Evaluation

JavaScript Object

- Not statically typed
  - Properties are added dynamically
  - Set of properties depends on control-flow

```
readGPS() {
  let loc = {};
  loc.long = getLongitude();
  loc.lat = getLatitude();
  if (hasAltitude())
    loc.alt = getAltitude();
  return loc;
}
```



long	174.8

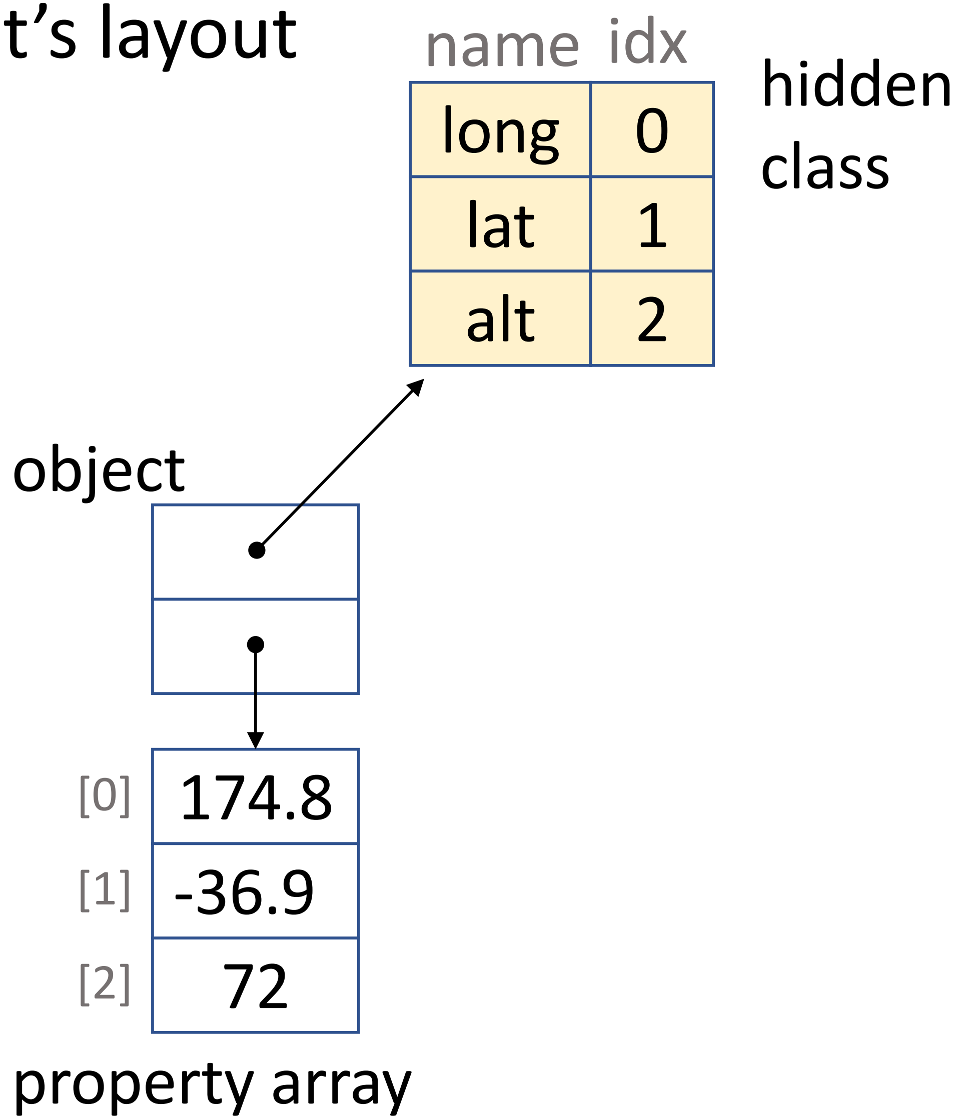
long	174.8
lat	-36.9

long	174.8
lat	-36.9
alt	72

Hidden Class (HC)

- Meta-object having object's layout
- object = (HC, prop array)

long	174.8
lat	-36.9
alt	72



hidden class

name	idx
long	0
lat	1
alt	2

object

property array

[0]	174.8
[1]	-36.9
[2]	72

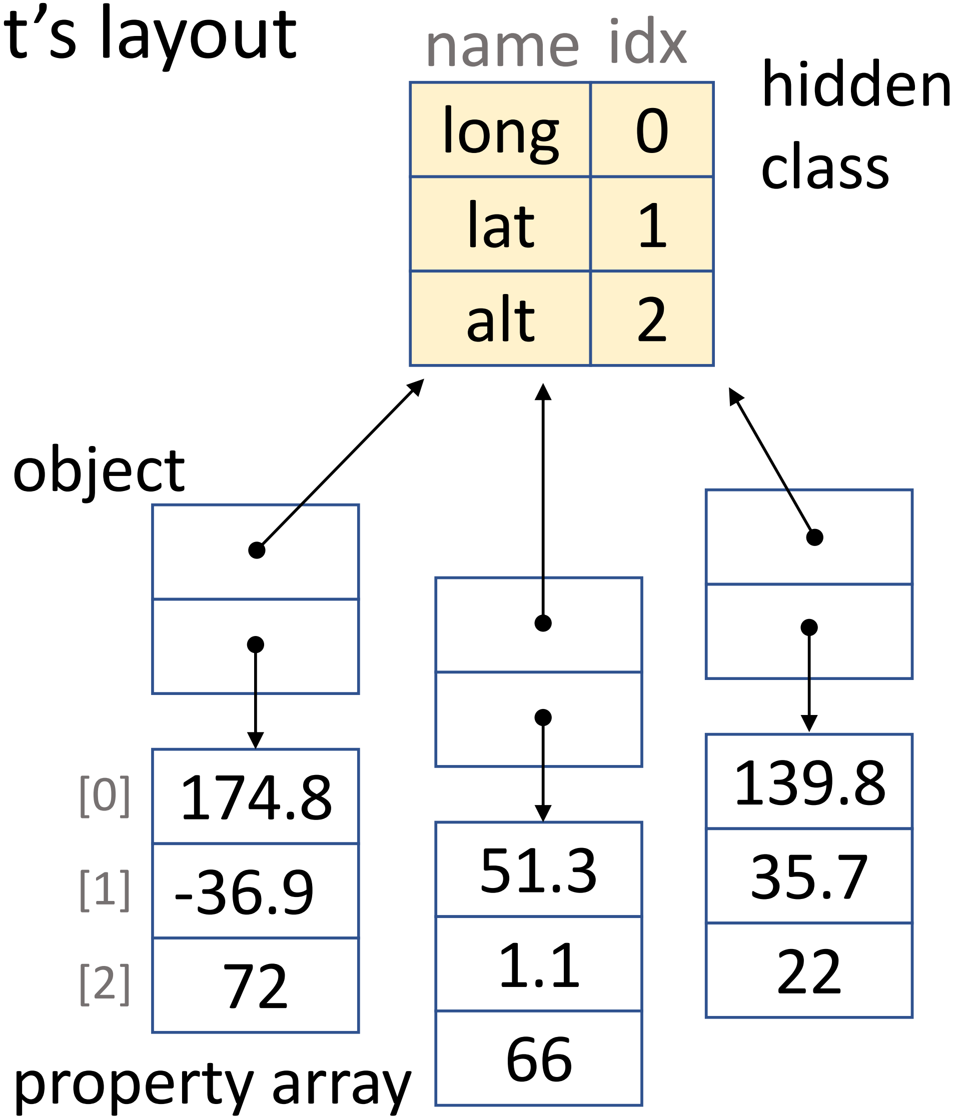
Hidden Class (HC)

- Meta-object having object’s layout
- object = (HC, prop array)
- Shared with all instances

long	174.8
lat	-36.9
alt	72

long	174.8
lat	35.7
alt	40

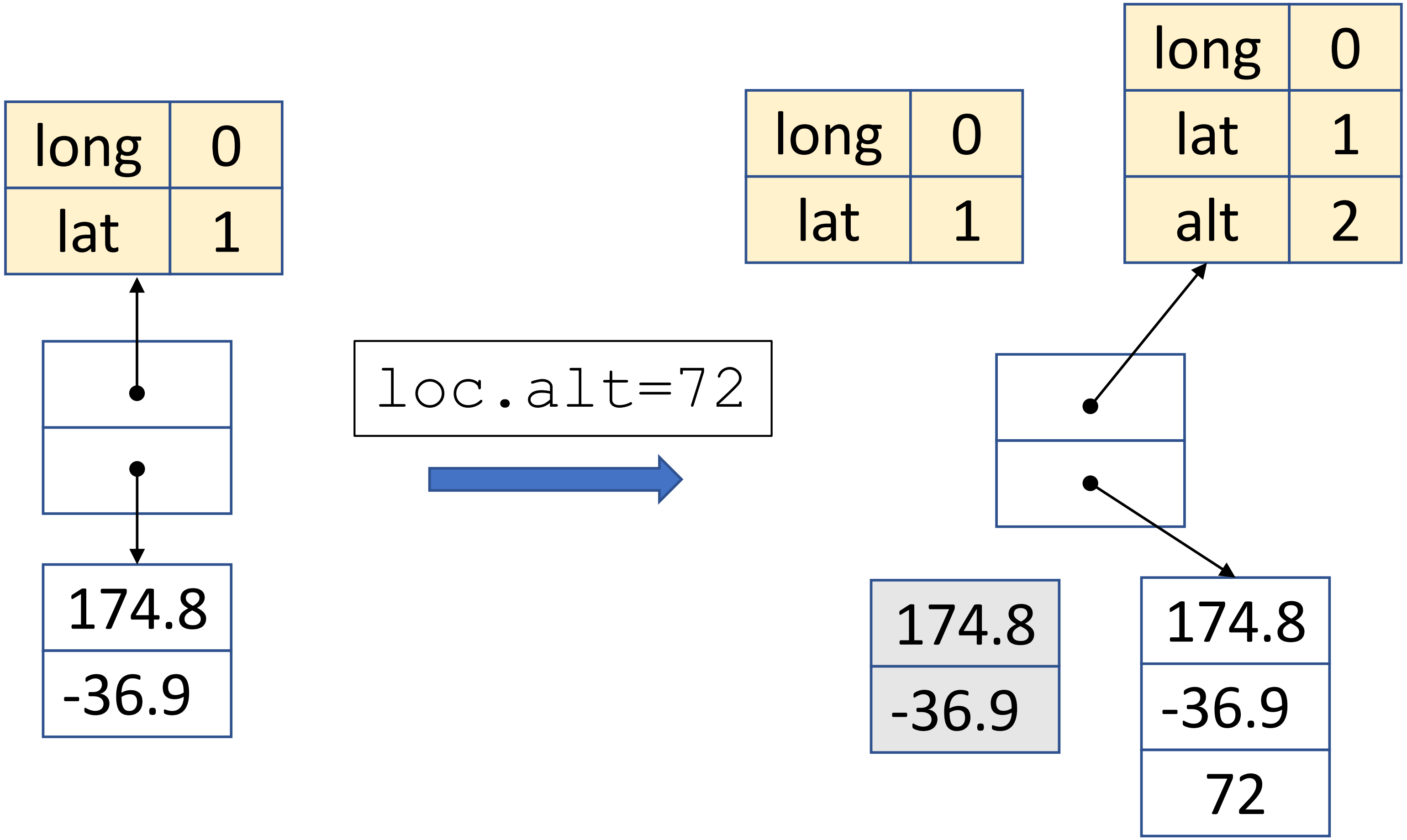
long	51.3
lat	1.1
alt	66



name	idx
long	0
lat	1
alt	2

Hidden Class Transition

- Adding new property causes HC transition
  - Find next HC, or create it if it has not been created
  - Re-allocate property array



long	0
lat	1

```
loc.alt=72
```

long	0
lat	1

long	0
lat	1
alt	2

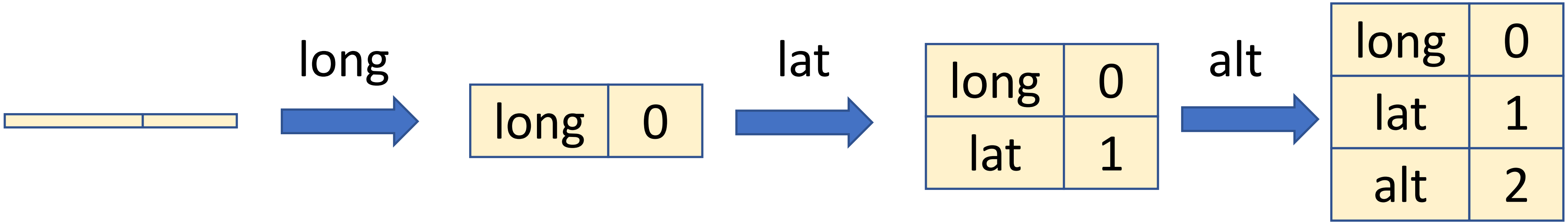
174.8
-36.9

174.8
-36.9

174.8
-36.9
72

Hidden Class Graph

- Hidden class graph (HCG) enables to find next HC quickly
    - node: HC
    - edge: transition labelled with property name



long

long	0

lat

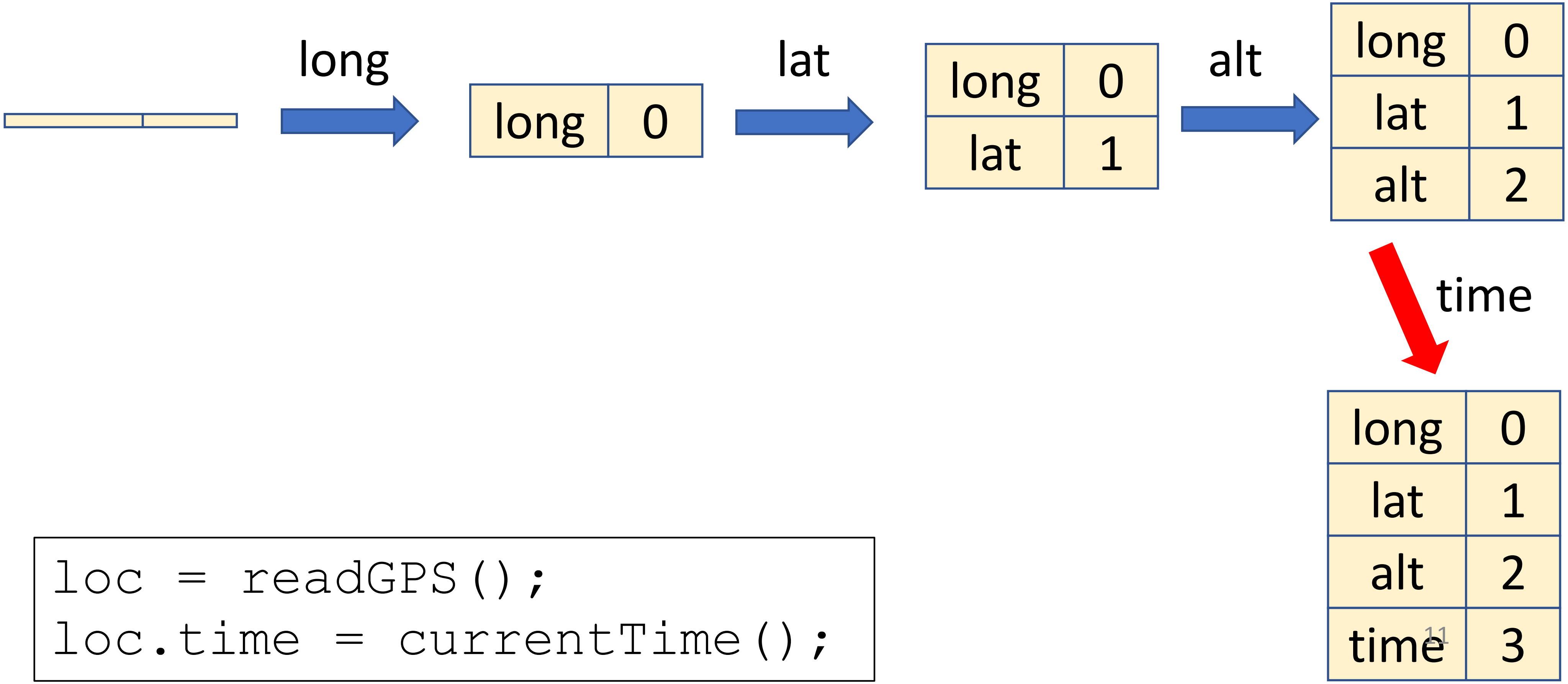
long	0
lat	1

alt

long	0
lat	1
alt	2

HCG grows during execution

- New property creates new HC
- New HC is added to HCG



long	0

long	0
lat	1

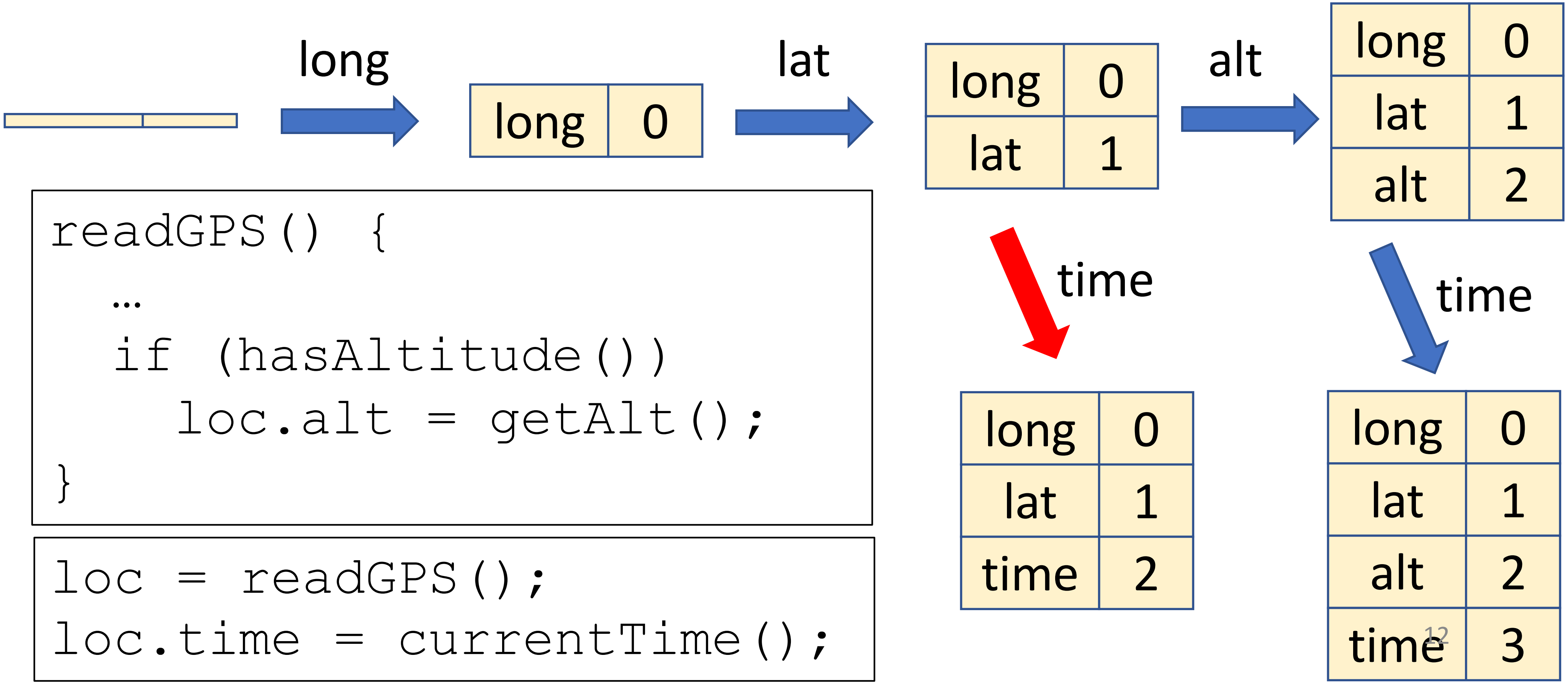
long	0
lat	1
alt	2

long	0
lat	1
alt	2
time	3

```
loc = readGPS();
loc.time = currentTime();
```

HCG grows during execution

- New property creates new HC
- New HC is added to HCG



```
readGPS() {
  …
  if (hasAltitude())
    loc.alt = getAlt();
}
```

```
loc = readGPS();
loc.time = currentTime();
```

long	0

long	0
lat	1

long	0
lat	1
alt	2

long	0
lat	1
time	2

long	0
lat	1
alt	2
time	3

Agenda

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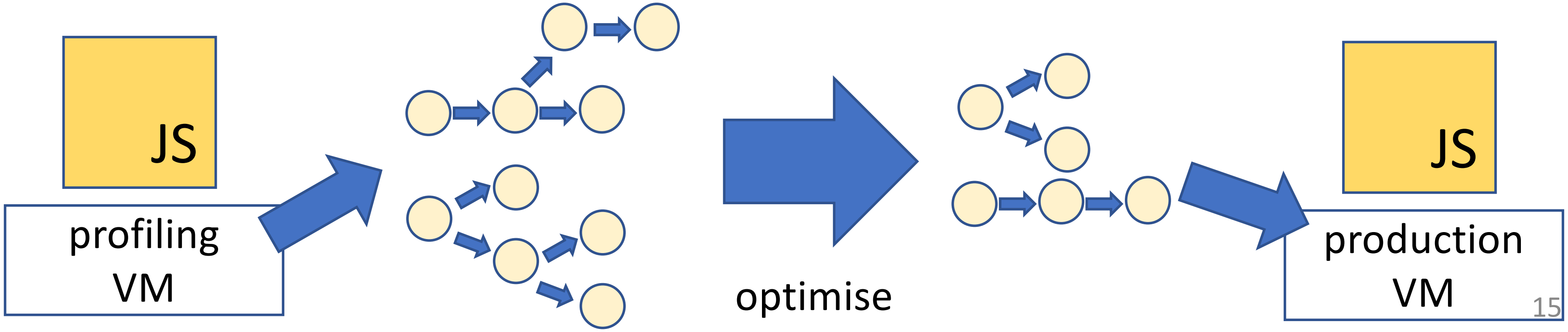
Offline Optimisation of HCG

- Optimise HCG with the following policy
  - Reduce memory footprint
    - Shrink HCG and reduce object size
  - Allow small space-inefficiency for speed
- Use optimised HCG in production VM
  - Run-time optimisation relying on assumption that HCG is stable

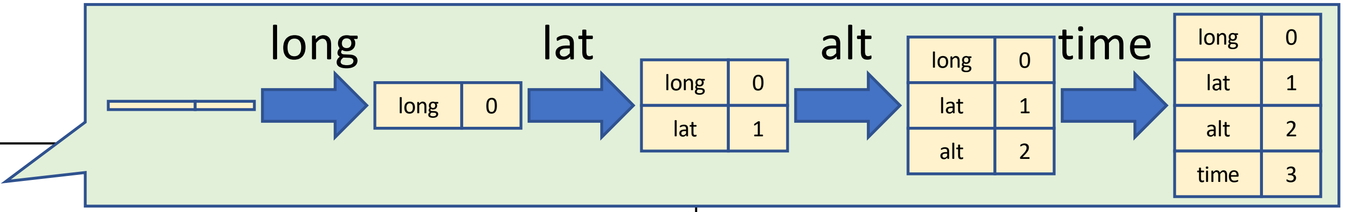


Optimisations

1. Eliminating intermediate HCs
2. Moving branches

Layout-monomorphic allocation site

- 95.8 % of allocation sites are layout-monomorphic
- Layout-monomorphic allocation site:
  all objects allocated there obtain the same set of properties in the same order
  - Eventually get transitions to the same HC



long

long	0

lat

long	0
lat	1

alt

long	0
lat	1
alt	2

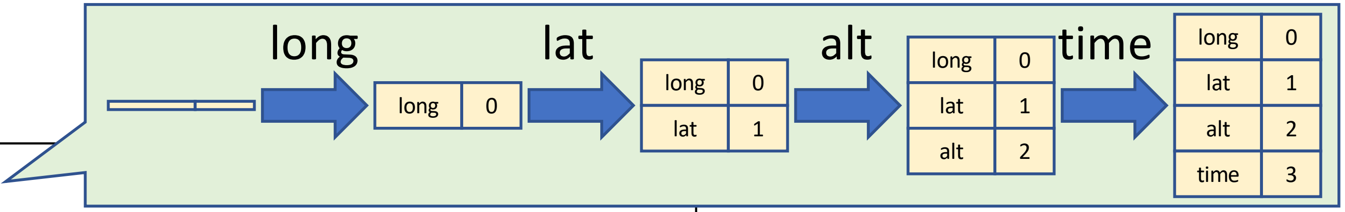
time

long	0
lat	1
alt	2
time	3

```
let loc = {};
loc.long = getLongitude();
loc.lat  = getLatitude();
loc.alt  = getAltitude();
loc.time = getCurrentTime();
```

Optimisation for layout-monomorphism: pre-transitioning

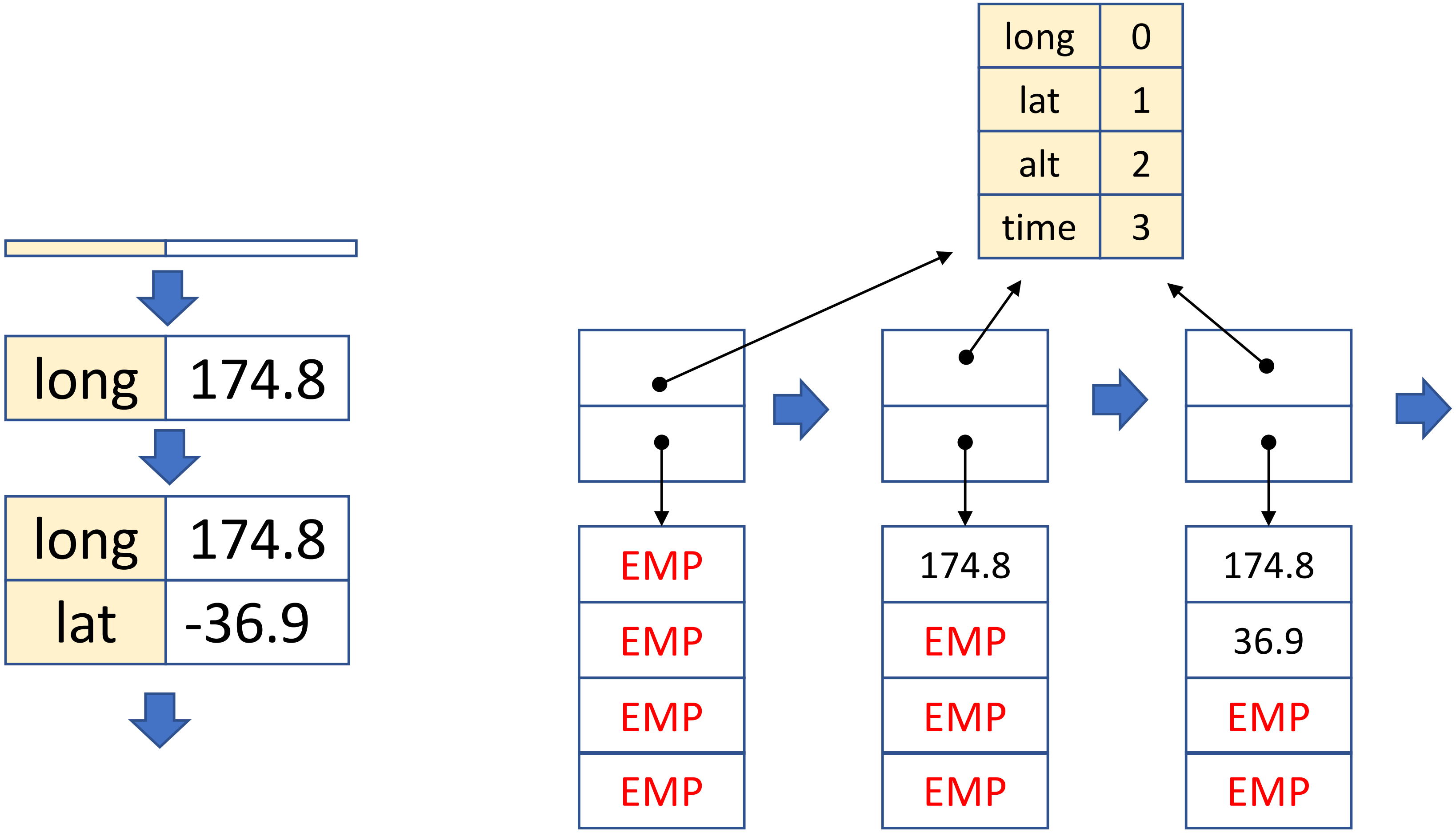
- Eliminate all hidden classes but the last from HCG
- Objects are created with their final layout
  - No re-allocation overhead of property array



```
let loc = {};
loc.long = getLongitude();
loc.lat  = getLatitude();
loc.alt  = getAltitude();
loc.time = getCurrentTime();
```

EMPTY value

- Initialise property array slots with EMP to indicate absence of the property
  - Allow us to search for property in the prototype object.



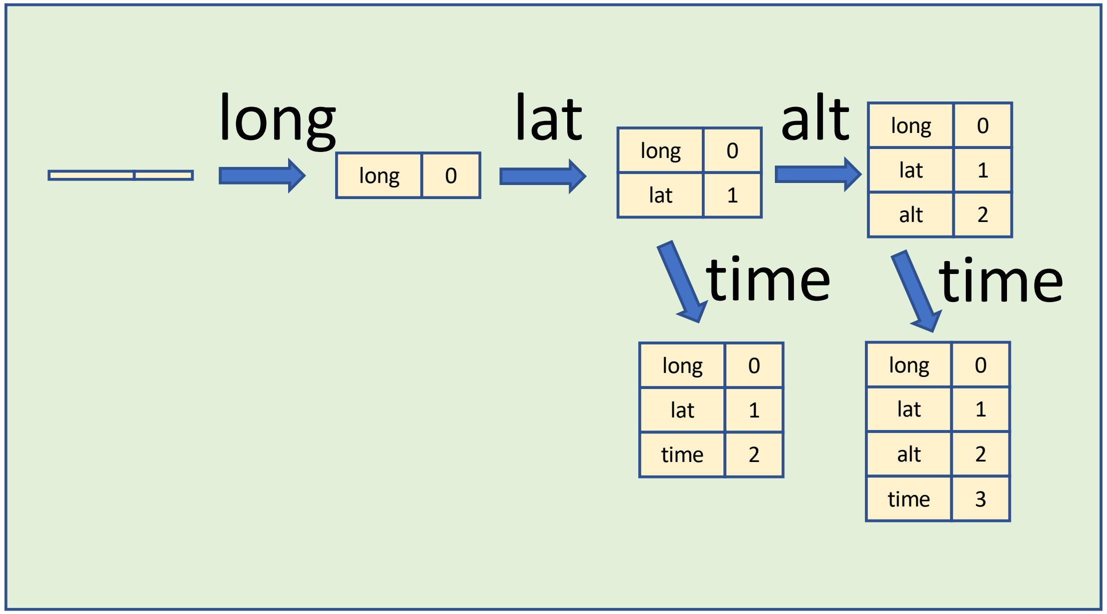
long	0
lat	1
alt	2
time	3

long	174.8

long	174.8
lat	-36.9

Optimisation 1: elimination of Intermediate HCs

- Generalization of pre-transitioning
- Eliminate all internal nodes but branching nodes



Optimisation 1: elimination of Intermediate HCs

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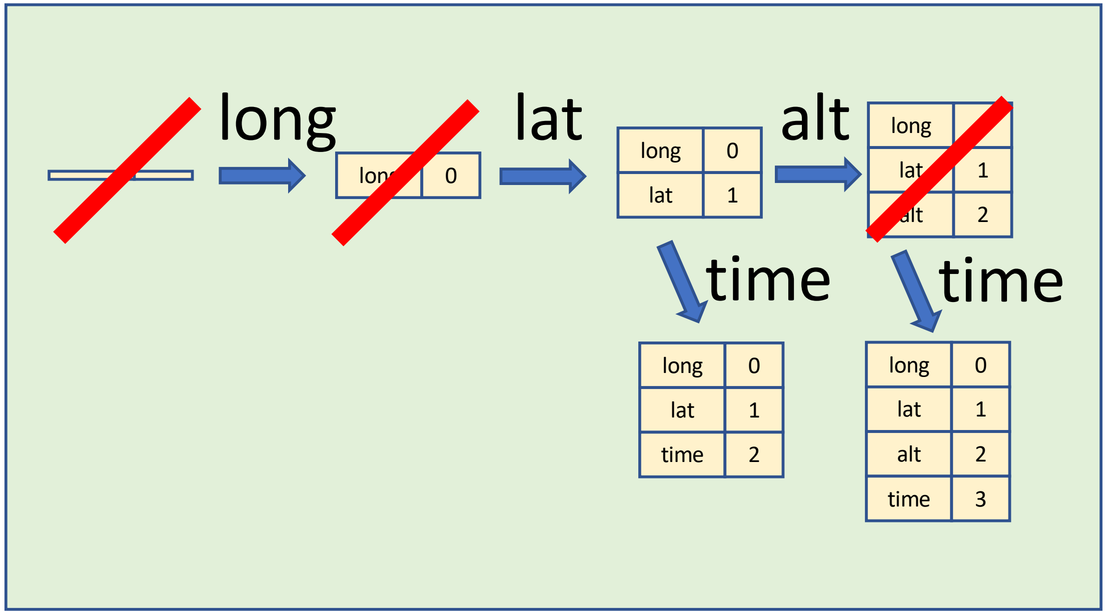
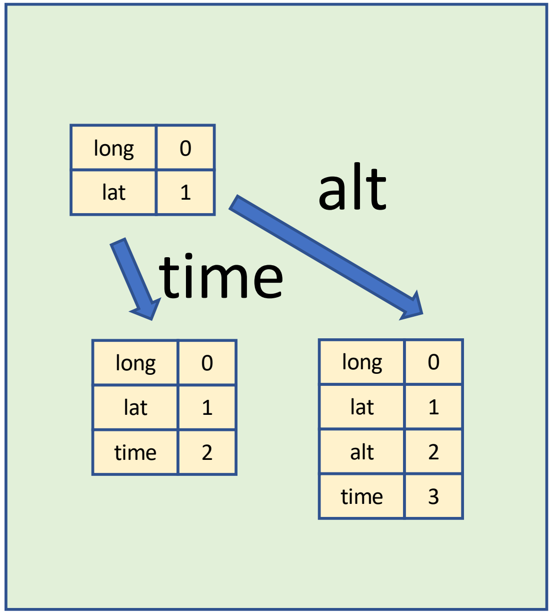
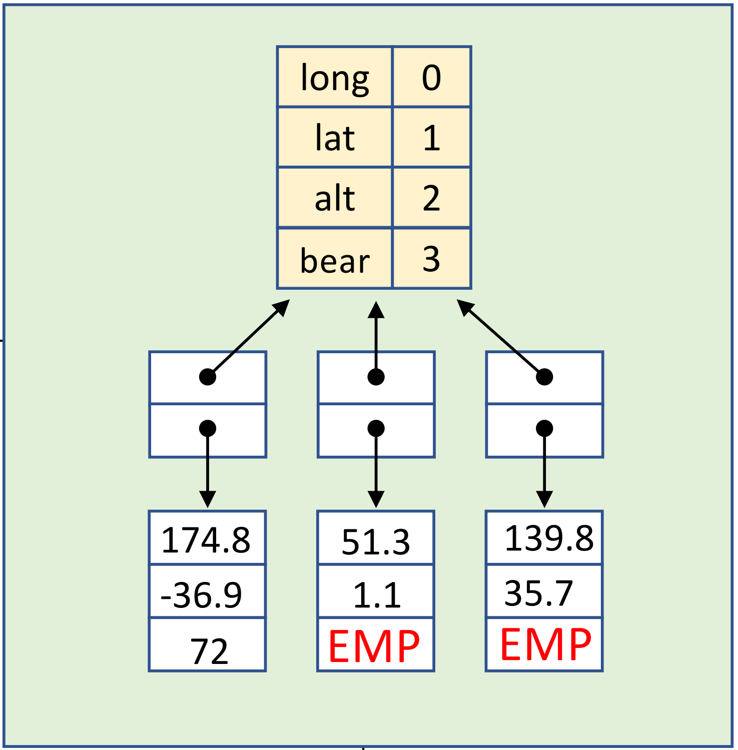




Over-allocation

- Aggressive elimination increases memory footprint
  - Memory for all possible properties are reserved
- Examples
  - Parts of objects get extra props
  - Props are added in the future

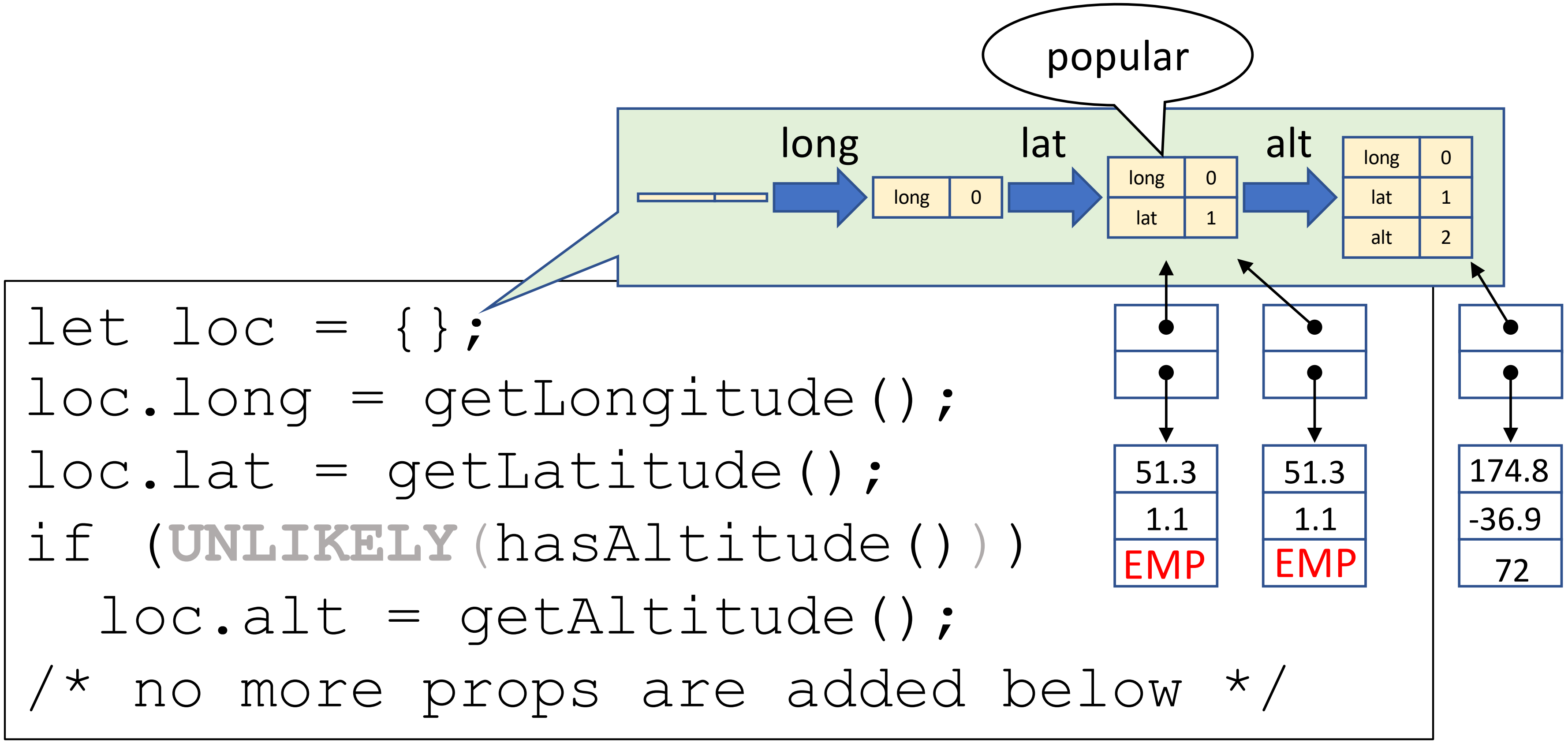


```
let loc = {};
loc.long = getLongitude();
loc.lat = getLatitude();
if (UNLIKELY(hasAltitude()))
  loc.alt = getAltitude();
/* no more props are added below */
```

Optimisation 1’: preserve popular HCs

- popular HC: $\max_{t \in execution} (\#\text{of instances}) > K$
  - Sample # of instances at each GC cycle

$K = 10$



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loc.long = getLongitude();
loc.lat = getLatitude();
if (UNLIKELY(hasAltitude()))
  loc.alt = getAltitude();
/* no more props are added below */
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Optimisation 1’: preserve popular HCs

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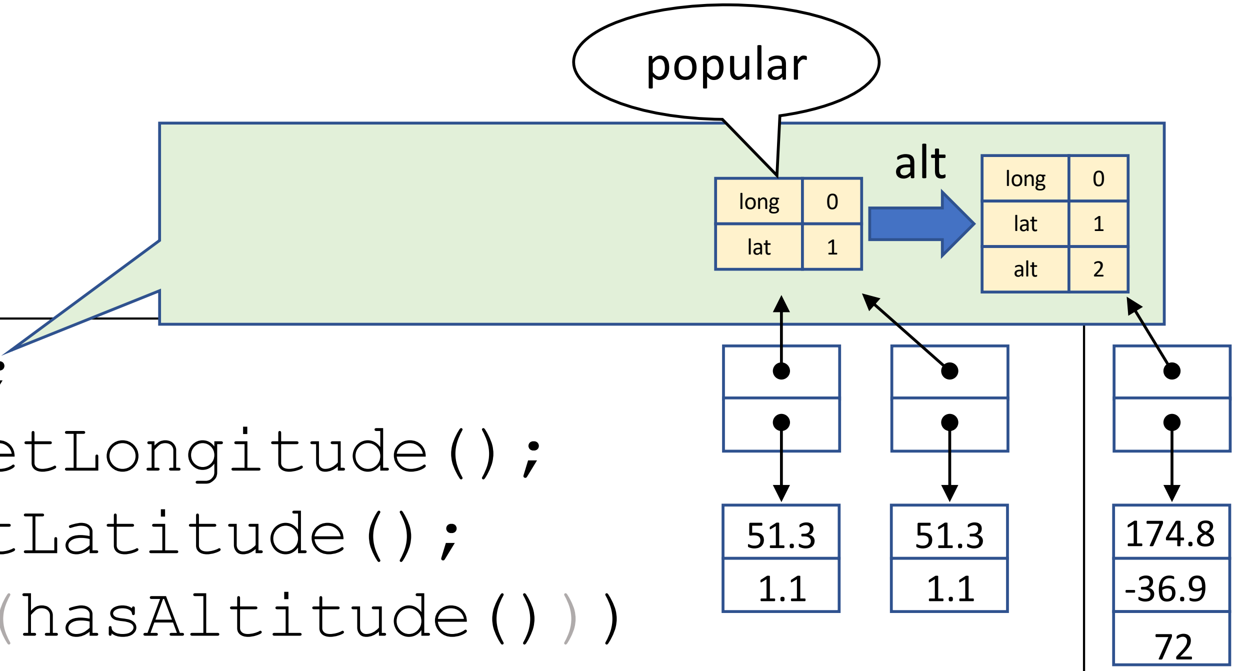
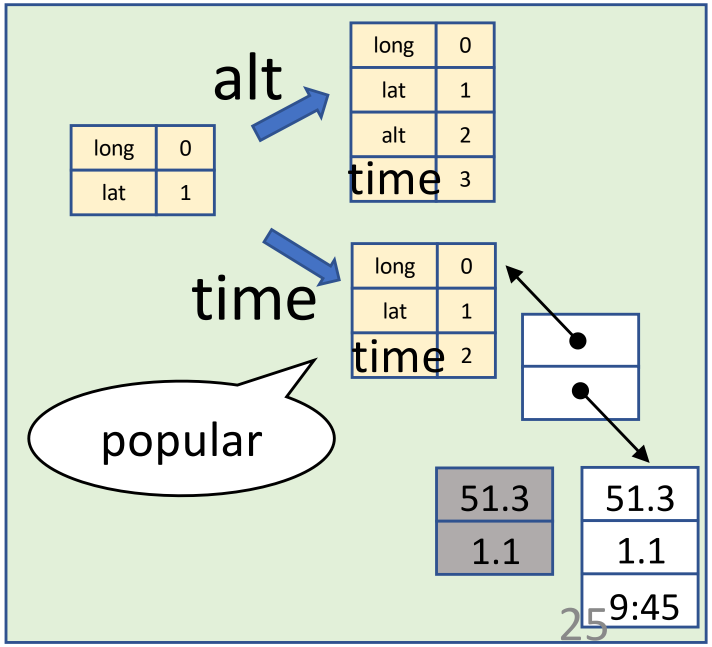


```
let loc = {};
loc.long = getLongitude();
loc.lat = getLatitude();
if (UNLIKELY(hasAltitude()))
  loc.alt = getAltitude();
/* no more props are added below */
```

Motivating example for optimisation 2

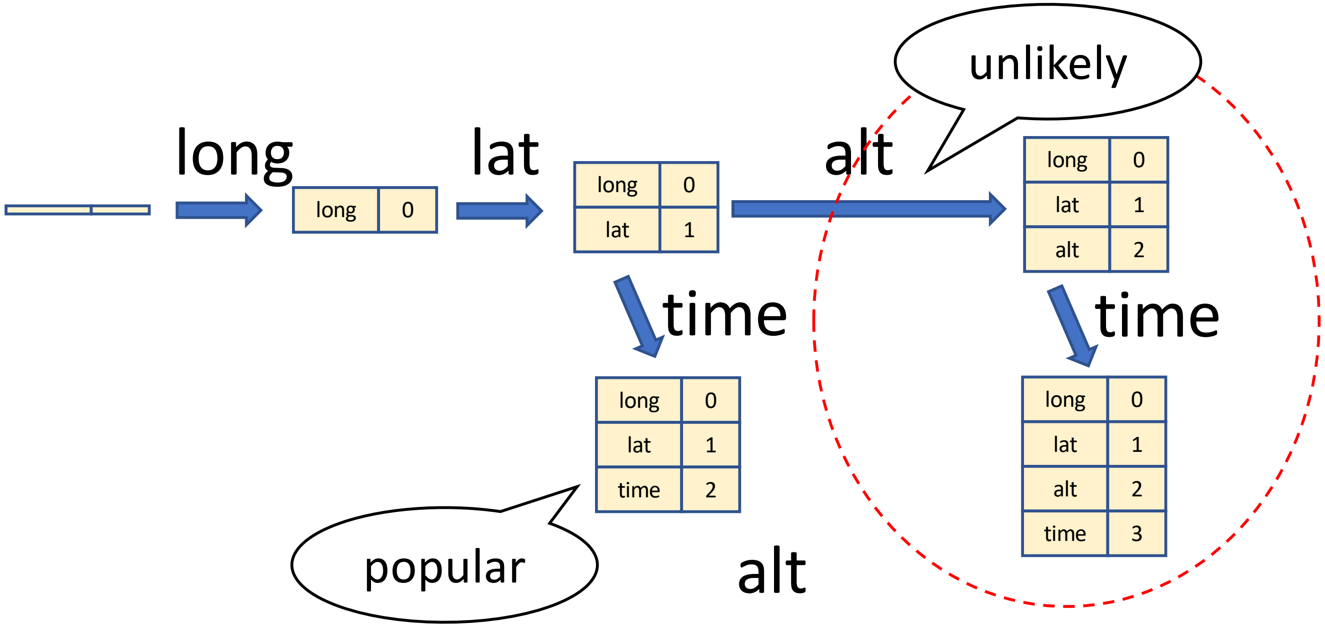
- Common properties are added after a branch
- Every object experiences property array re-allocation

```
let loc = {};
loc.long = getLongitude();
loc.lat = getLatitude();
if (UNLIKELY(hasAltitude()))
  loc.alt = getAltitude();
loc.time = currentTime();
```



Optimisation 2: moving branches

- Move “unlikely” branch before optimization 1



long	0

long	0
lat	1

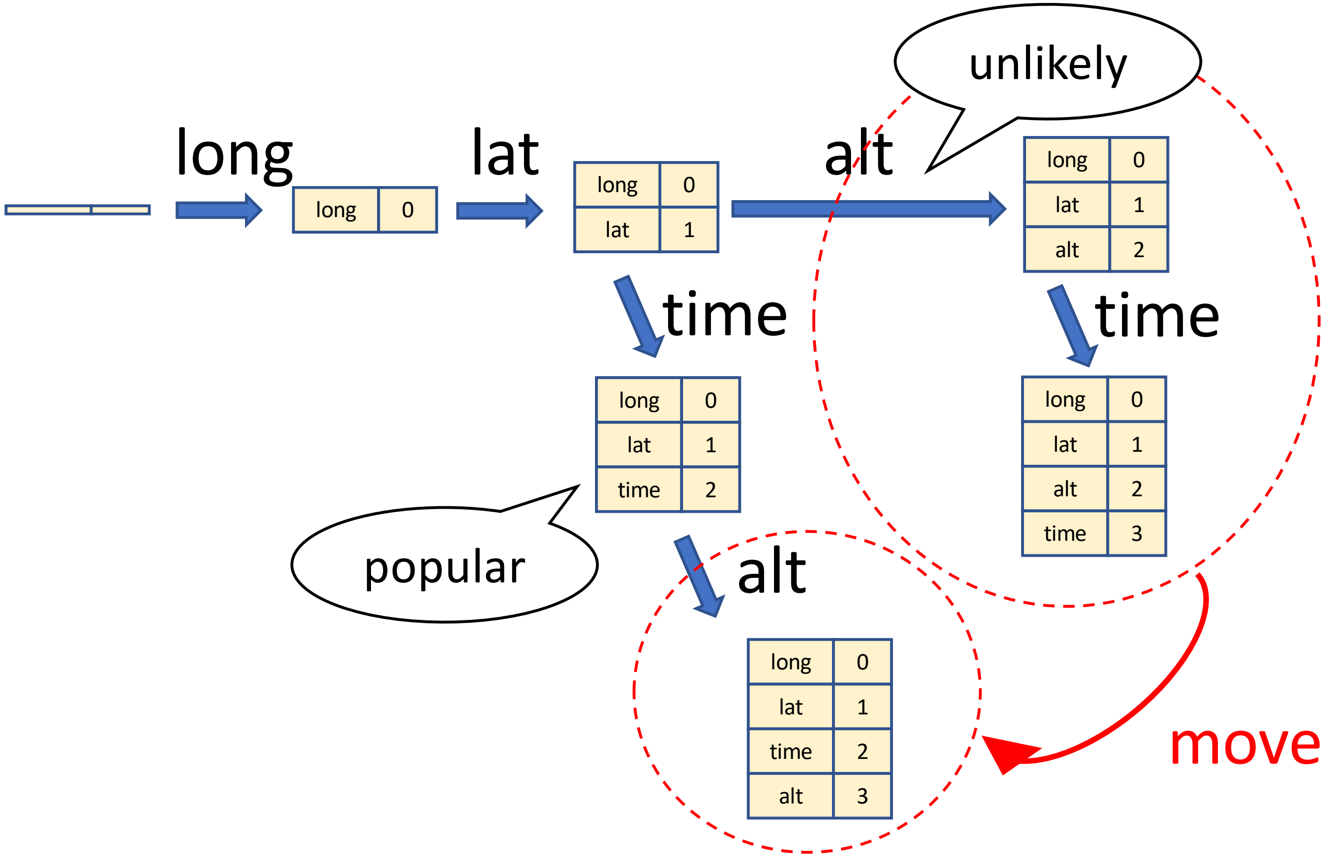
long	0
lat	1
alt	2

long	0
lat	1
time	2

long	0
lat	1
alt	2
time	3

Optimisation 2: moving branches

- Move “unlikely” branch before optimization 1



long	0

long	0
lat	1

long	0
lat	1
alt	2

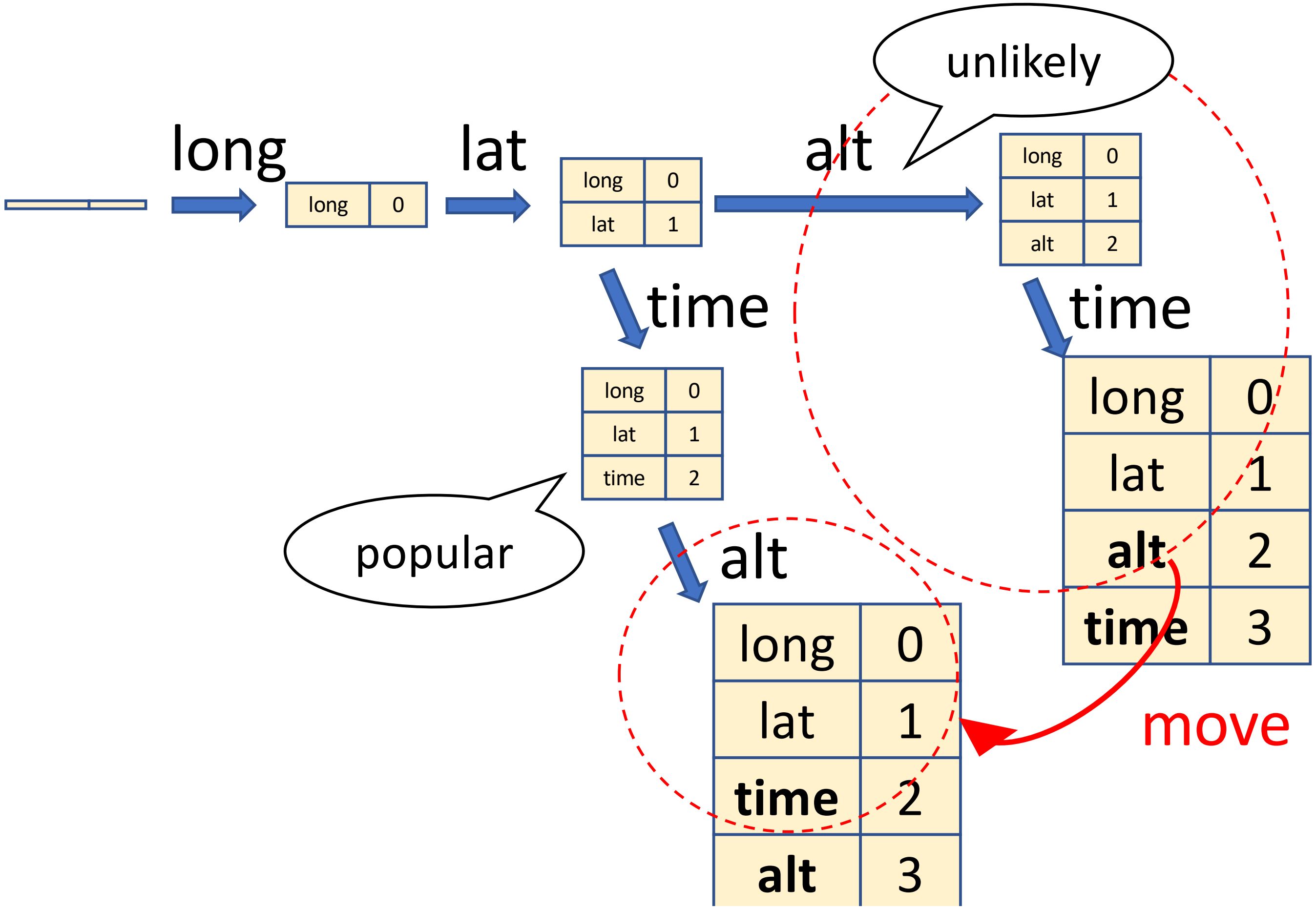
long	0
lat	1
time	2

long	0
lat	1
alt	2
time	3

long	0
lat	1
time	2
alt	3

Optimisation 2: moving branches

- Move “unlikely” branch before optimization 1



long	0

long	0
lat	1

long	0
lat	1
alt	2

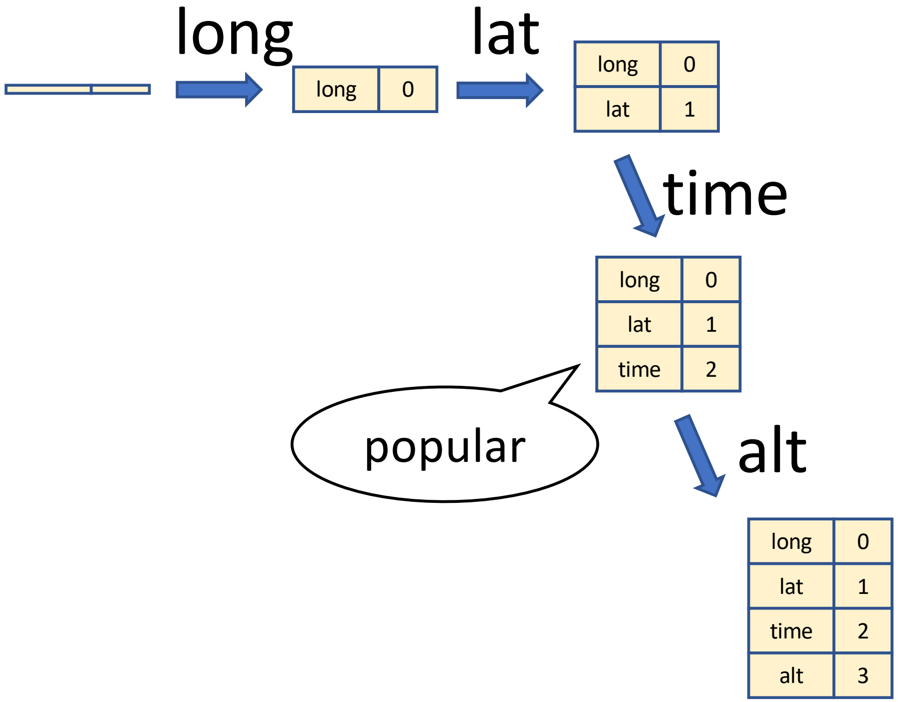
long	0
lat	1
time	2

long	0
lat	1
alt	2
time	3

long	0
lat	1
time	2
alt	3

Optimisation 2: moving branches

- Move “unlikely” branch before optimization 1
  - Linearise HCG



long

long	0

lat

long	0
lat	1

time

long	0
lat	1
time	2

popular

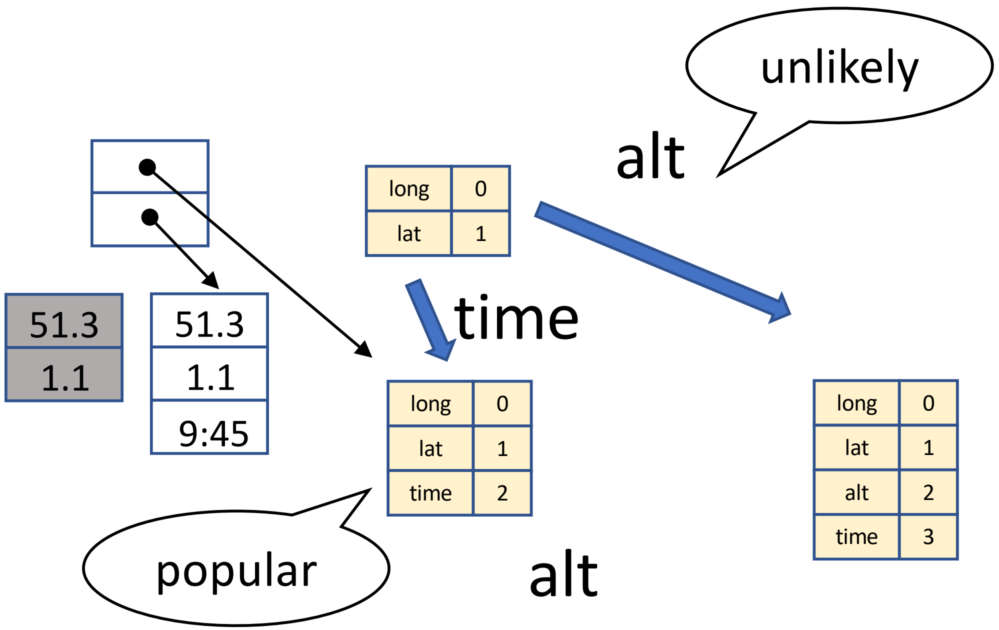
alt

long	0
lat	1
time	2
alt	3

Benefits of moving branches

- Encourage elimination of intermediate HCs
- Majority of objects are created with final layout

without moving branches



51.3	
1.1	

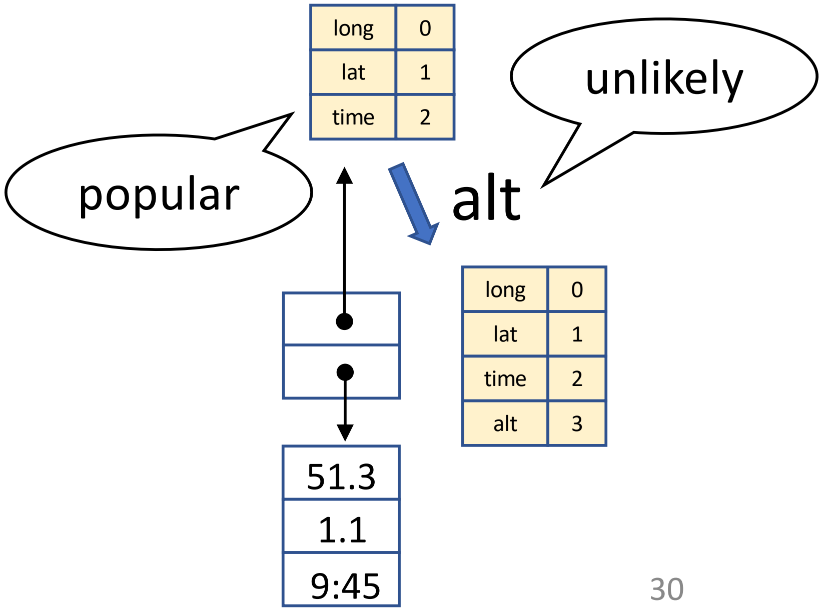
51.3	
1.1	
9:45	

long	0
lat	1

long	0
lat	1
time	2

long	0
lat	1
alt	2
time	3

with moving branches



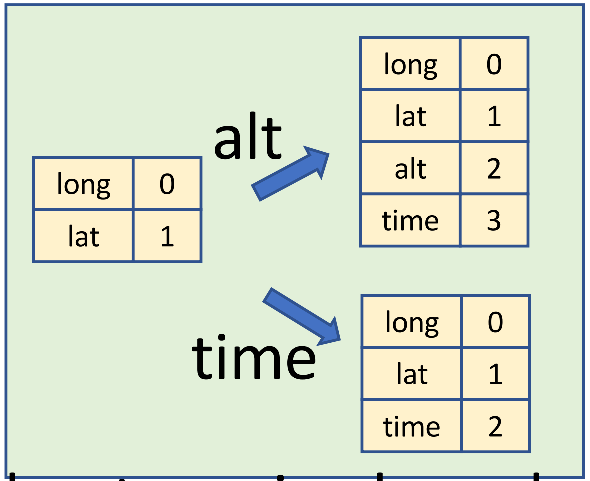
long	0
lat	1
time	2

long	0
lat	1
time	2
alt	3

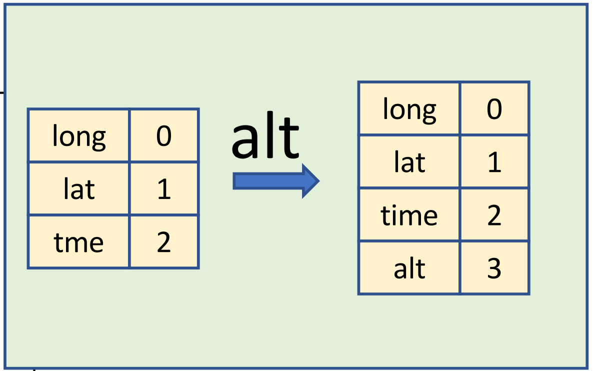
51.3
1.1
9:45

Benefits of moving branches to inline cache

- Moving branch reduces variations of HCs
- Improves inline cache hit ratio
  - inline cache gives index if object has the same HC as cached



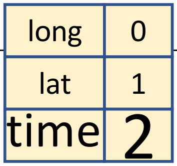
without moving branches



with moving branches

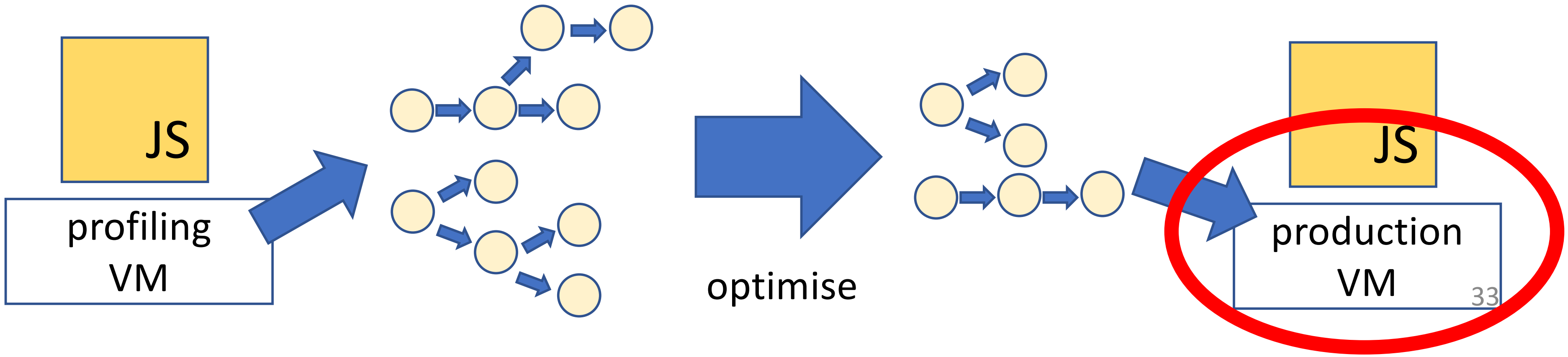
```
localTime(loc) {
  tdiff = floor(loc.long / 15);
  return loc.time + tdiff;
}
```

```
if (obj->HC ==           )
  return obj->props[2];
else
  slow_path();
```



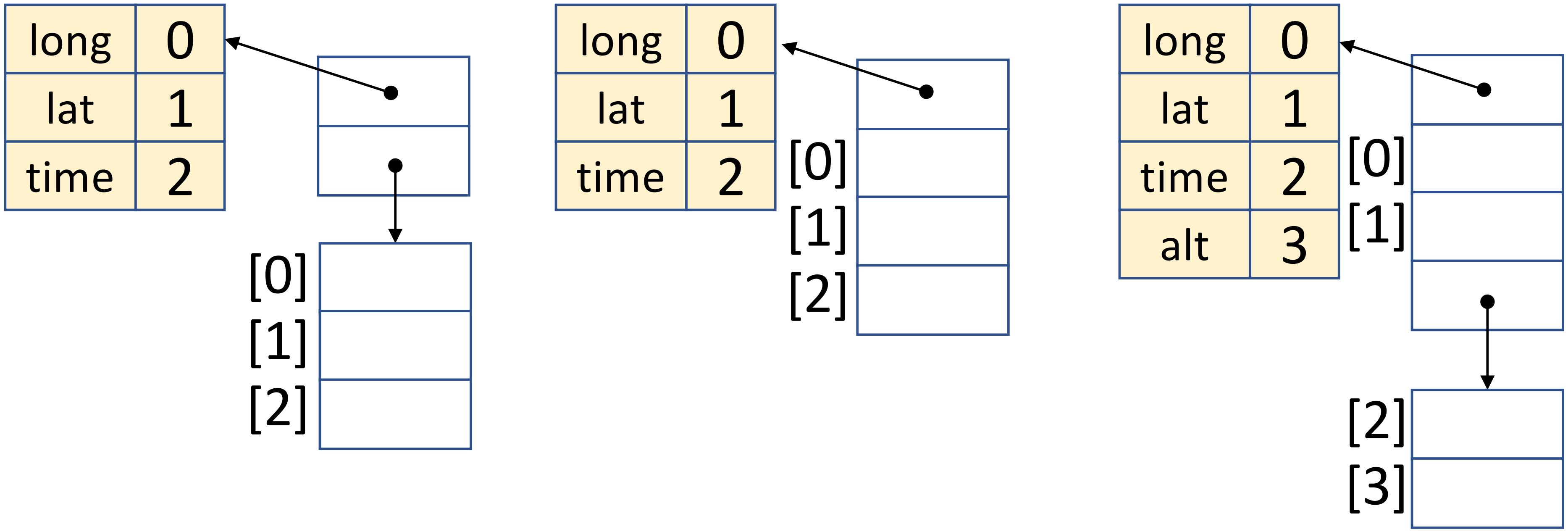
Run-time optimisation

- Run-time optimisation relying on assumption that HCG is stable
  - in-object allocation
  - baking HCG into flash memory (future work)



in-object allocation

- Allocate all properties *in* object
  - Save space for indirect pointer
- In case of overflow,
  convert the last property area to indirect pointer

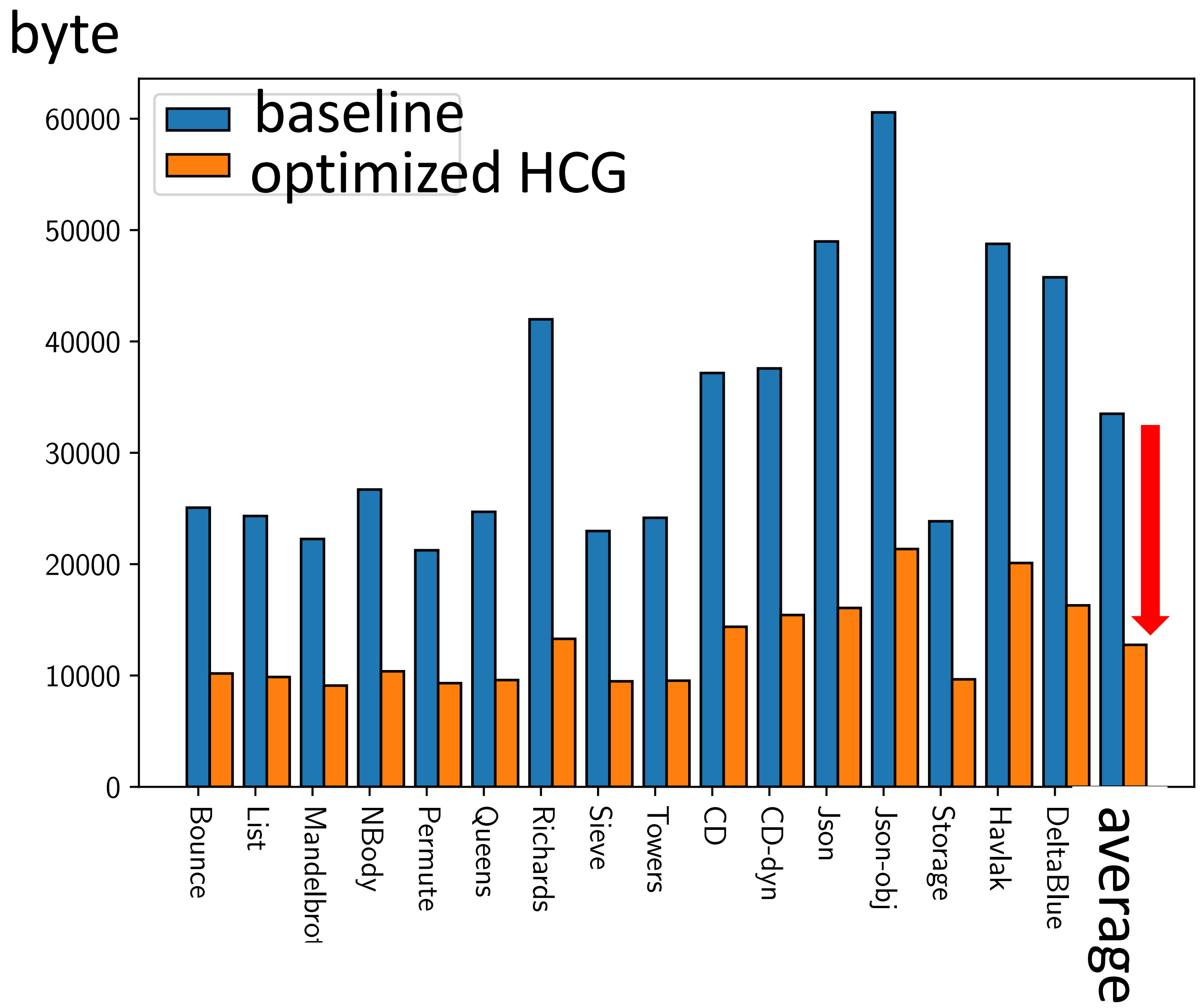


original version   in-object allocation   overflow

Evaluation

- Implemented in eJSVM
- Are we fast yet benchmarks
  - original benchmarks
  - JSON-obj: uses an AST node object as a dictionary
  - CD-dyn: do not initialise future properties with NULL

Size of HC-related data

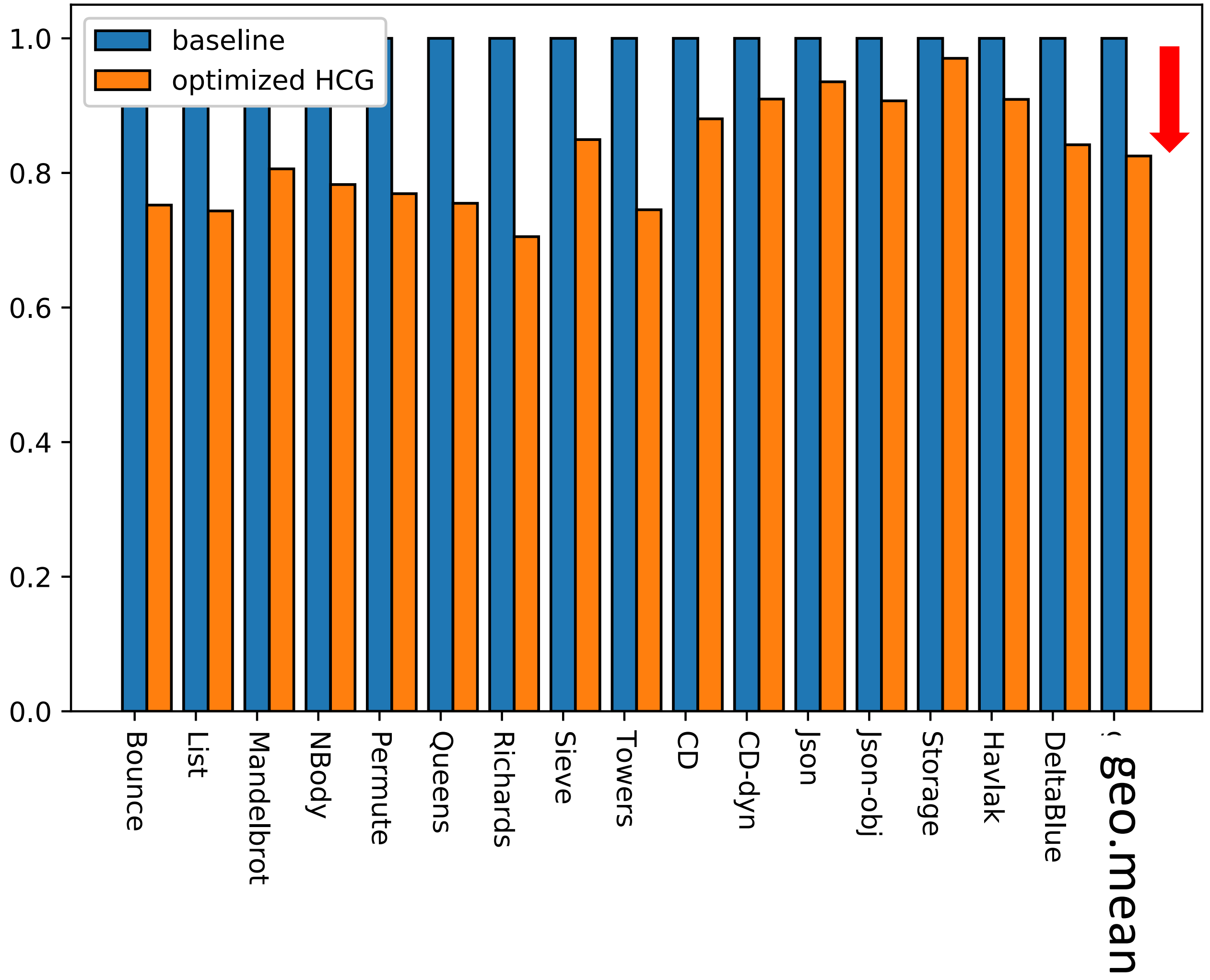


reduced by 61.9%
from 33.5 KB
to 12.8KB

nomadised

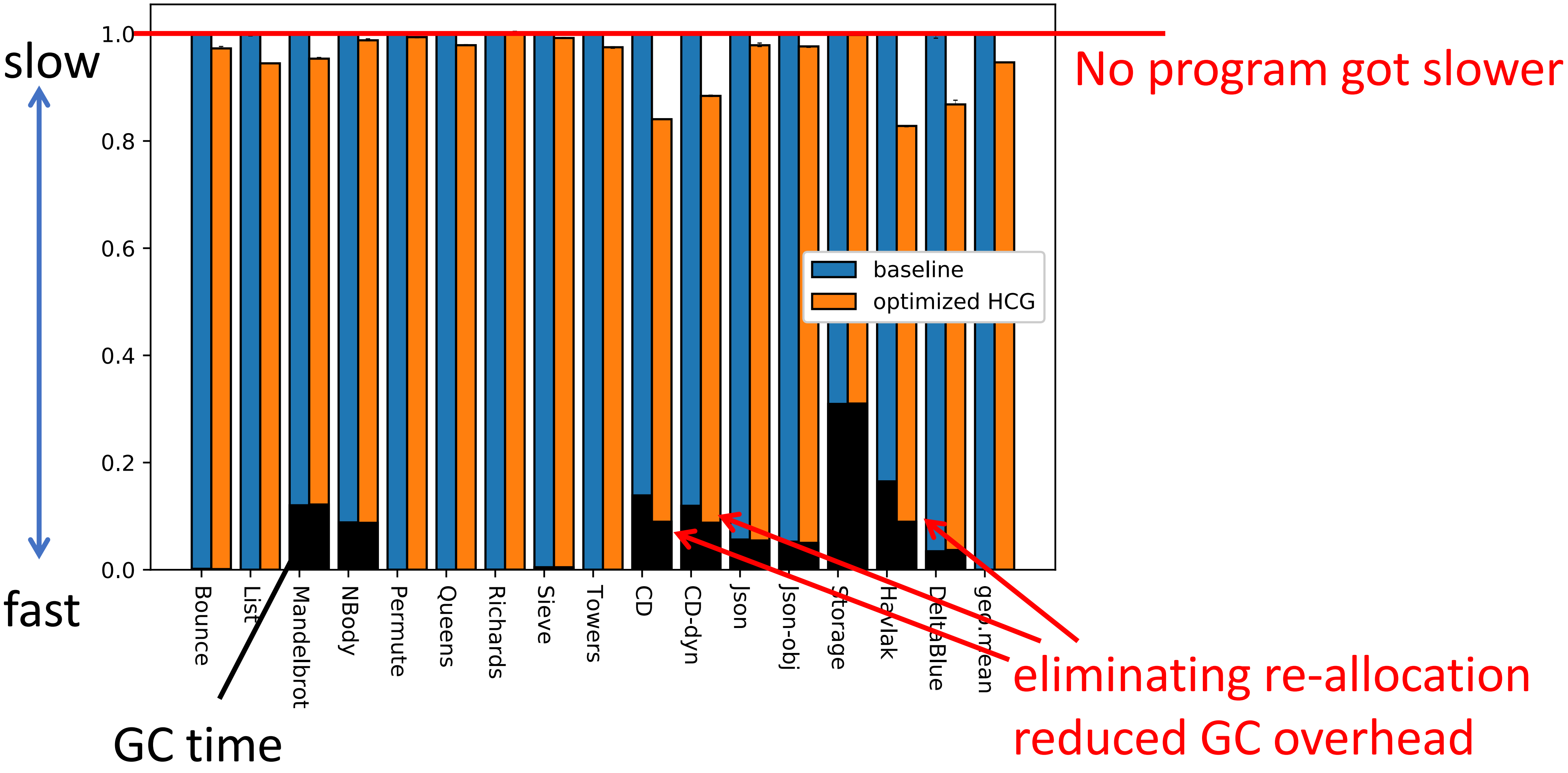
Maximum volume of all objects

including HC-related data



reduced by 17%

Normalised elapsed time

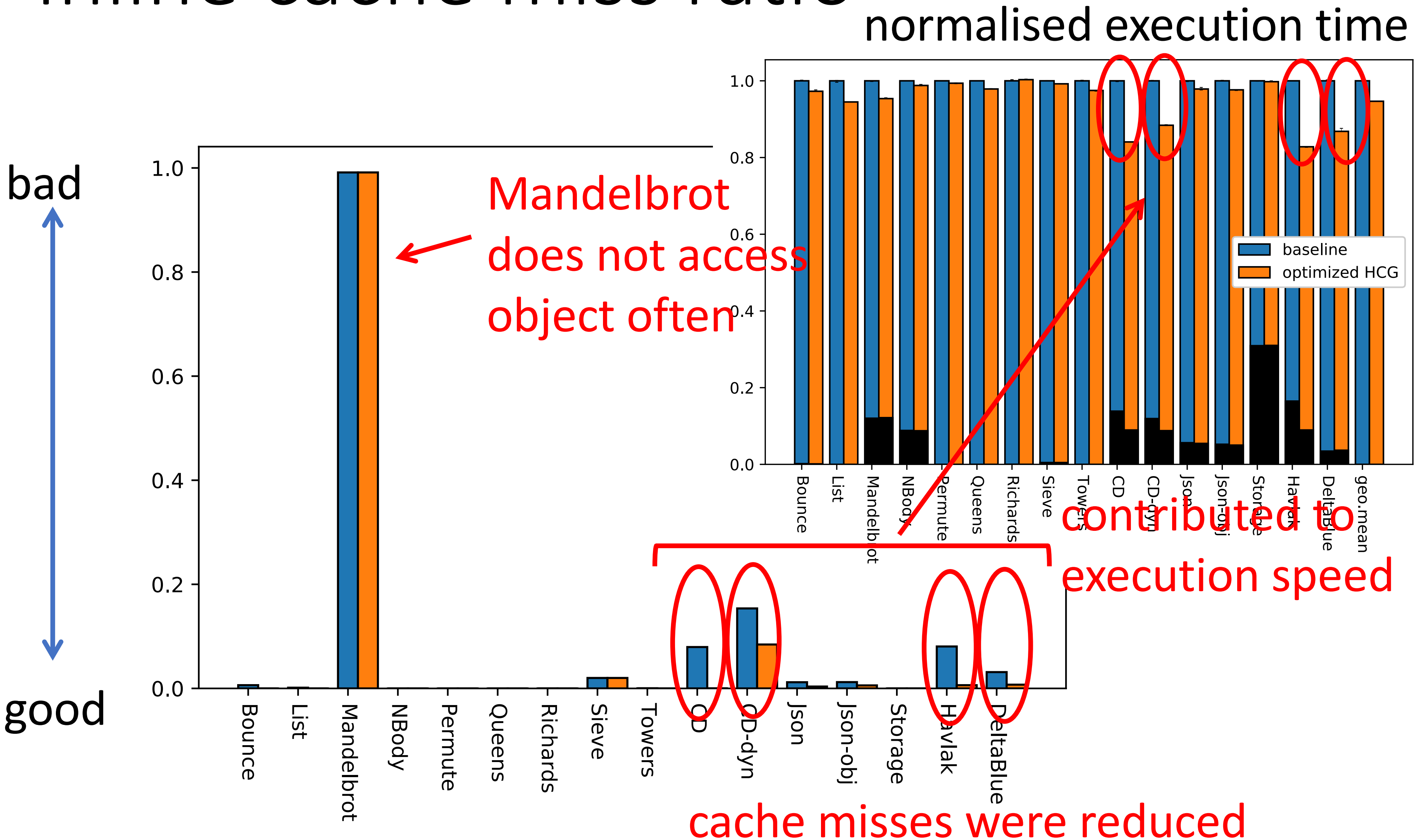


GC time

No program got slower

eliminating re-allocation reduced GC overhead

Inline cache miss ratio



Mandelbrot does not access object often

contributed to execution speed

cache misses were reduced

Conclusion

- We proposed offline optimisation of HCG
    - Move “unlikely” branches
    - Eliminate intermediate HCs
        - preserve popular HCs
- Reduced HC-related data by 61.9% and footprint by 17%
- No program got slower
- Moving branches improved inline cache hit ratio