Kindergarten Cop:
Dynamic Nursery Resizing for GHC

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ParaPhrase Project: Parallel Patterns for Heterogeneous Multicore Systems (ICT-288570), 2011-2015, €4.2M budget

13 Partners, 8 European countries

UK, Italy, Germany, Austria, Ireland, Hungary, Poland, Israel

Coordinated by Kevin Hammond St Andrews

RePhrase Project: Refactoring Parallel Heterogeneous Software – a Software Engineering Approach
(ICT-644235), 2015-2018, €3.6M budget

8 Partners, 6 European countries
UK, Spain, Italy, Austria, Hungary, Israel

Coordinated by Kevin Hammond St Andrews

The Glorious Haskell Compiler (GHC)

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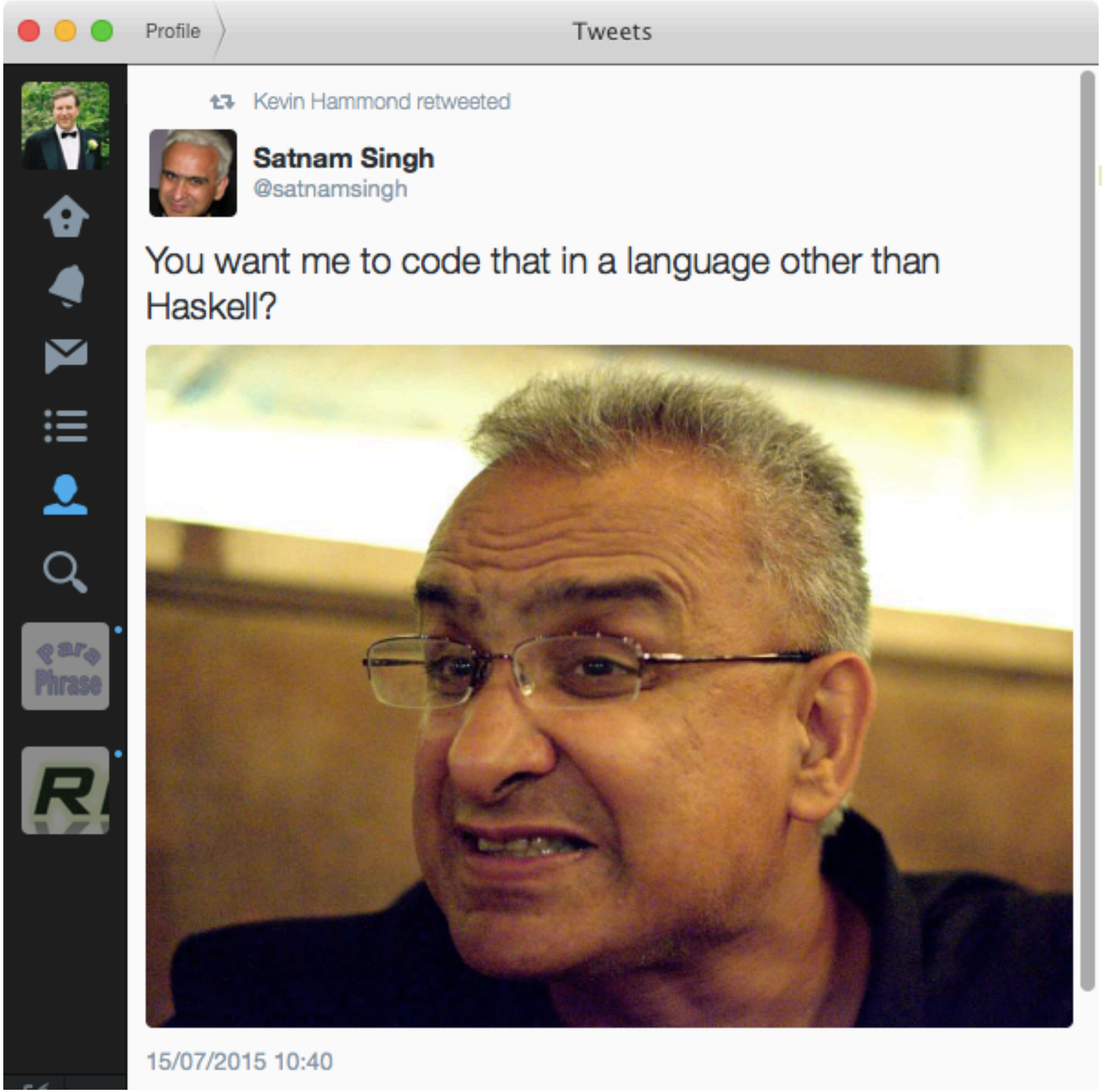
- The de-facto standard for Haskell
  - the non-strict functional language
- Originally, the Glasgow Haskell Compiler
  - now maintained at Microsoft Research

Haskell 98 Language and Libraries, the Revised Report
Simon Peyton Jones (ed.) ... Kevin Hammond ..
Cambridge University Press, 2003

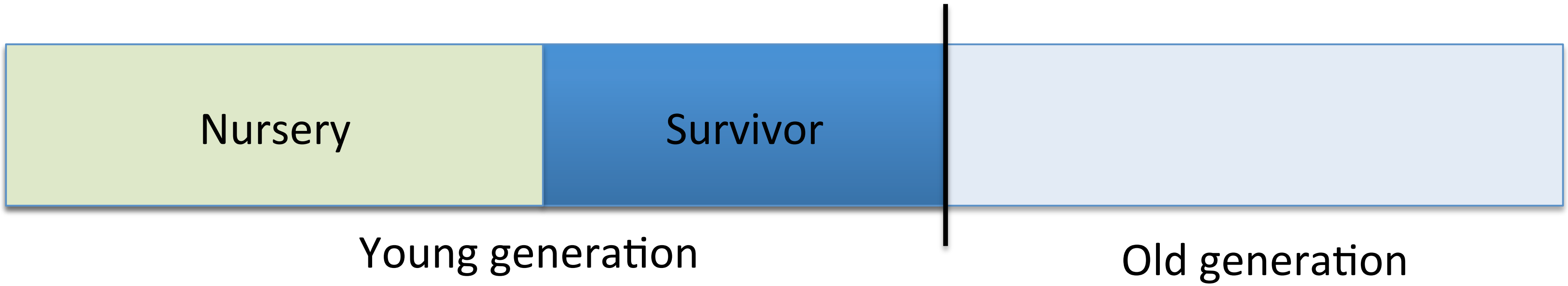
The Glasgow Haskell Compiler
`http://www.haskell.org/ghc`



Satnam Singh
Google

Generational garbage collection

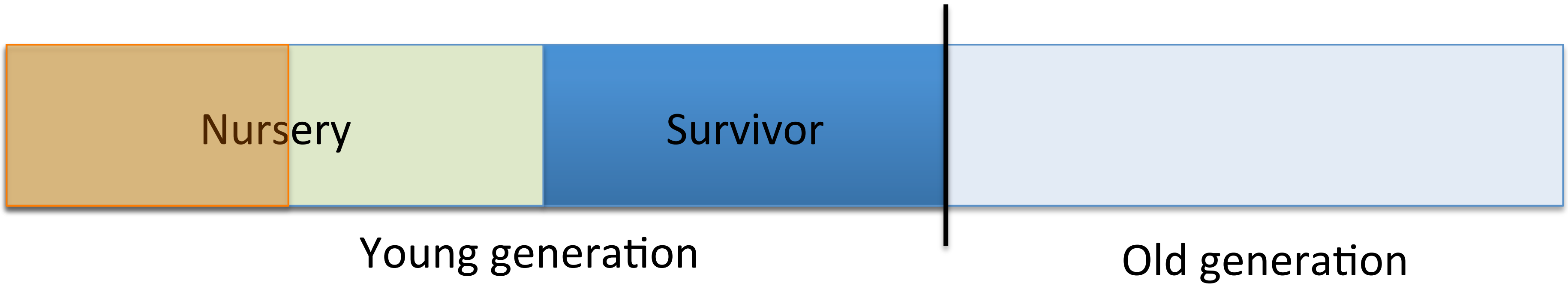
- GHC uses Appel-style generational garbage collection
  - Assumption: most of the allocated objects die young
- Heap divided into a number of generations
  - Usually two generations: young and old
  - Young generation divided into the nursery and the survivor area



A. W. Appel. Simple Generational Garbage Collection and Fast Allocation, Software: Practice and Experience,19:2, p. 171-182, 1989.

Generational garbage collection (2)

- New objects are (almost) always allocated in the nursery



Generational garbage collection (3)

- When the nursery becomes full, *minor collection* is triggered

- Live data is copied into the survivor area

- Data that survives a number of collections is promoted to the old generation
- When the old generation becomes full, *major collection* is triggered (whole heap is collected)

Generational garbage collection (4)

- Generational collectors are designed to do minor collections most of the time

- Performance heavily depends on the size of the nursery!
  - Smaller nursery size => better cache behaviour
  - Larger nursery size => fewer collections, collections less expensive
    - Cost of the garbage collection depends on the amount of live data, not garbage
  - Imperative languages: make nursery as large as possible!
  - Lazy functional languages: small nurseries

GHC Garbage Collection

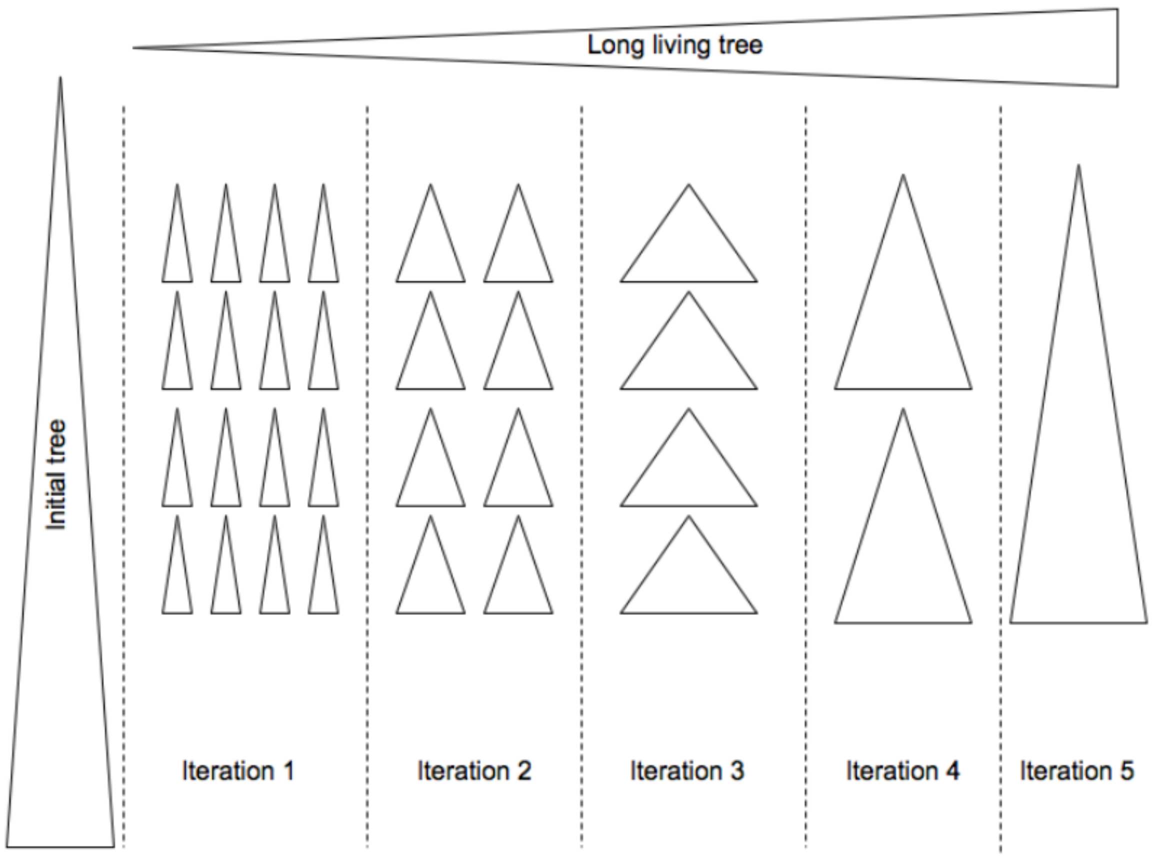
- Generational garbage collection, two generations
- Size of the nursery can be set to a constant (-A <size>)
  - or RTS can *dynamically* change nursery size after each collection (-H)
- Dynamic nursery resizing algorithm sets the nursery to have the largest "reasonable" size that is possible
  - After each garbage collection, the nursery size is set to be

$$\frac{H - N}{1 + p}$$

H – heap size, N – 2x size of the live data,

p – percentage of data copied from the nursery in the last collection

Binary-trees benchmark



Allocation size increases throughout program execution

Binary-trees memory behaviour

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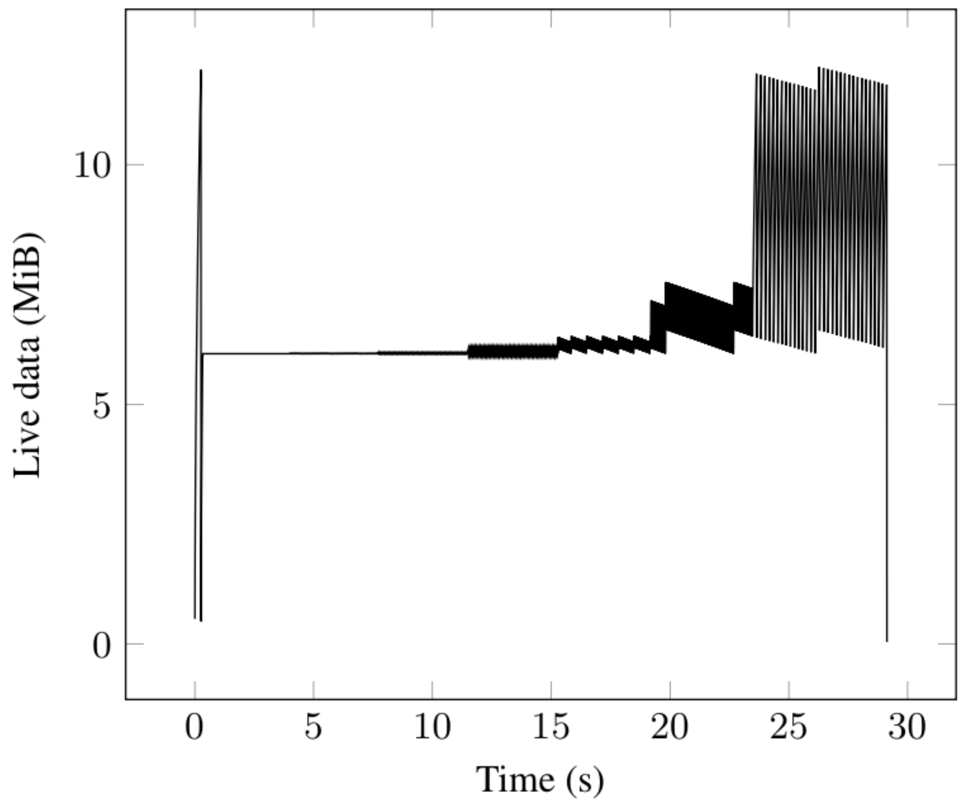
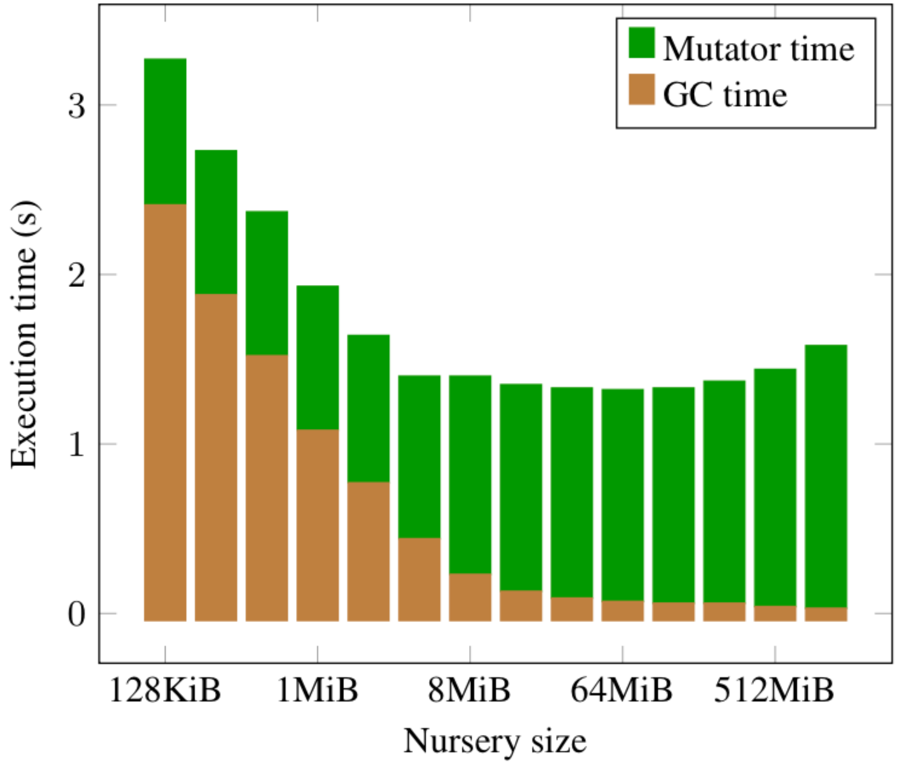


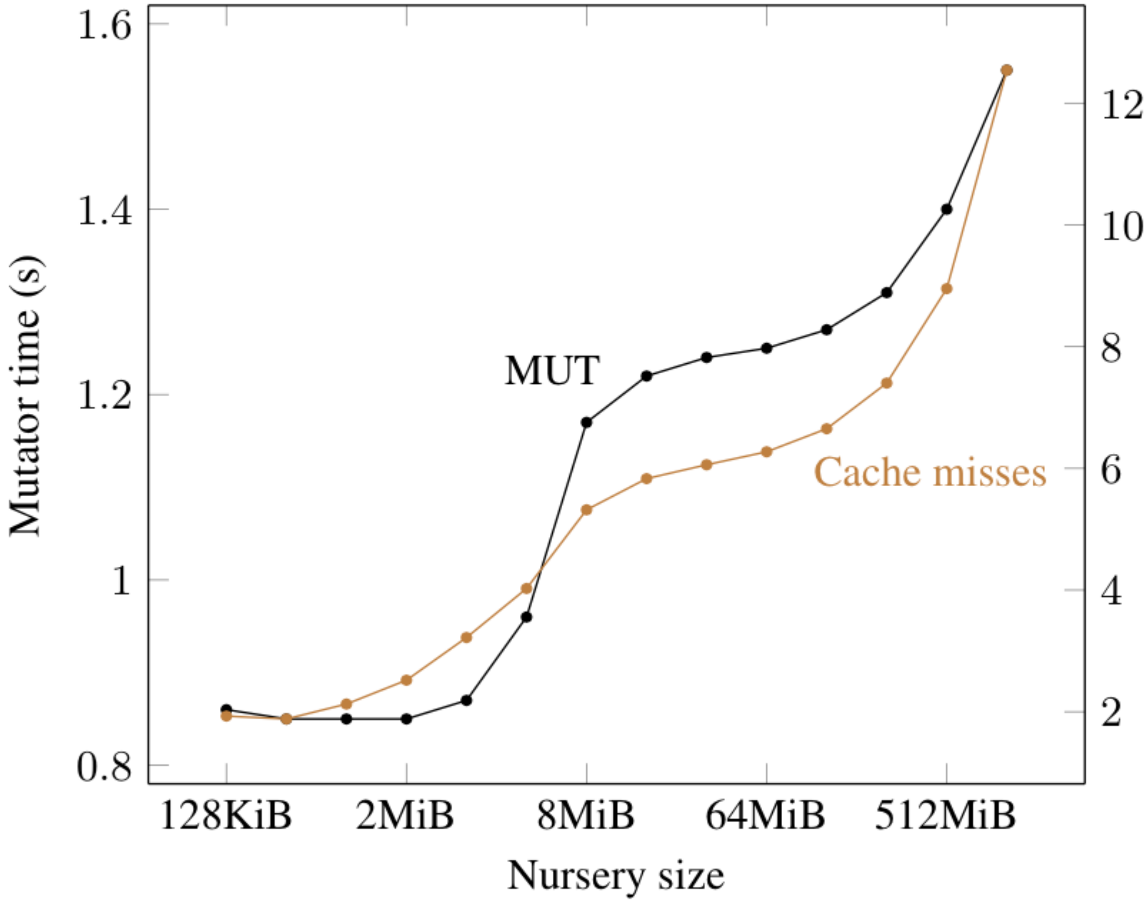
2.4GHz Intel i7 processor, 4Mb L2 Cache, 4GB RAM

Binary-trees with Constant-sized nurseries

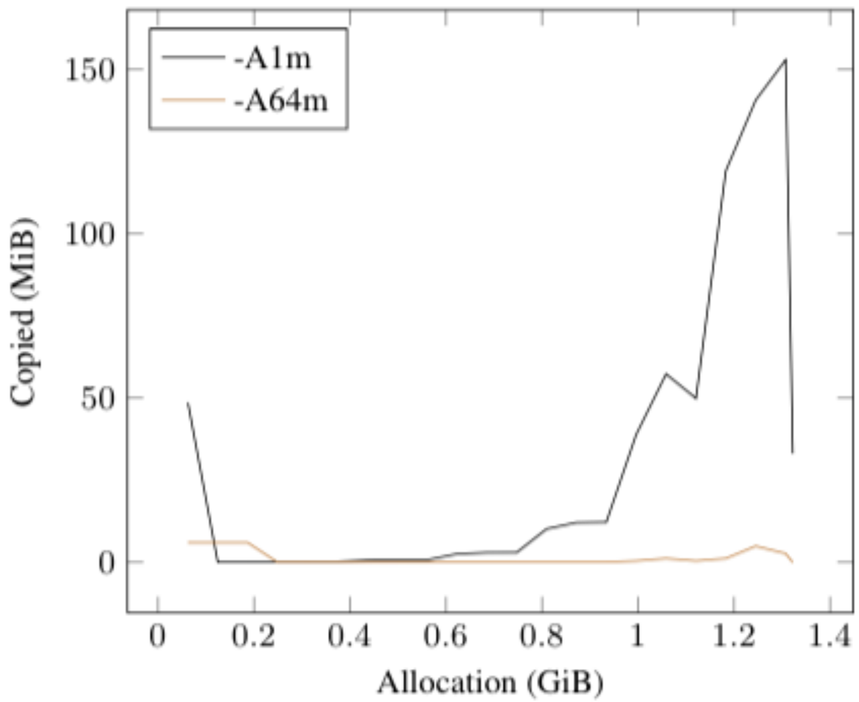


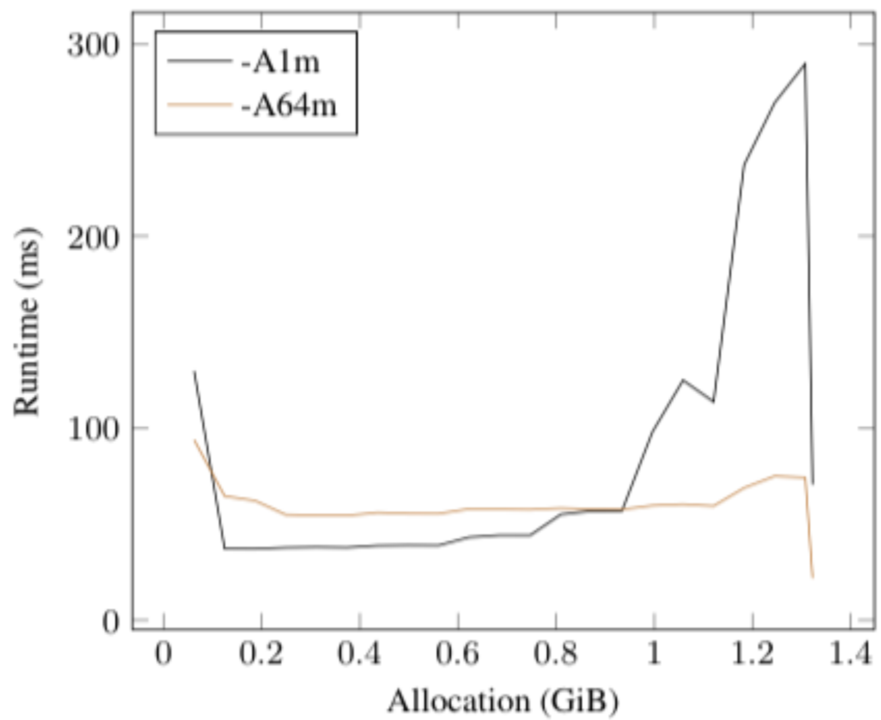
- The bigger the nursery , the less time is spent in garbage collection
  - however, evaluation (mutator) time is also increased

Why does mutator time increase?



Binary-trees phase analysis





(Nursery) Size Matters!

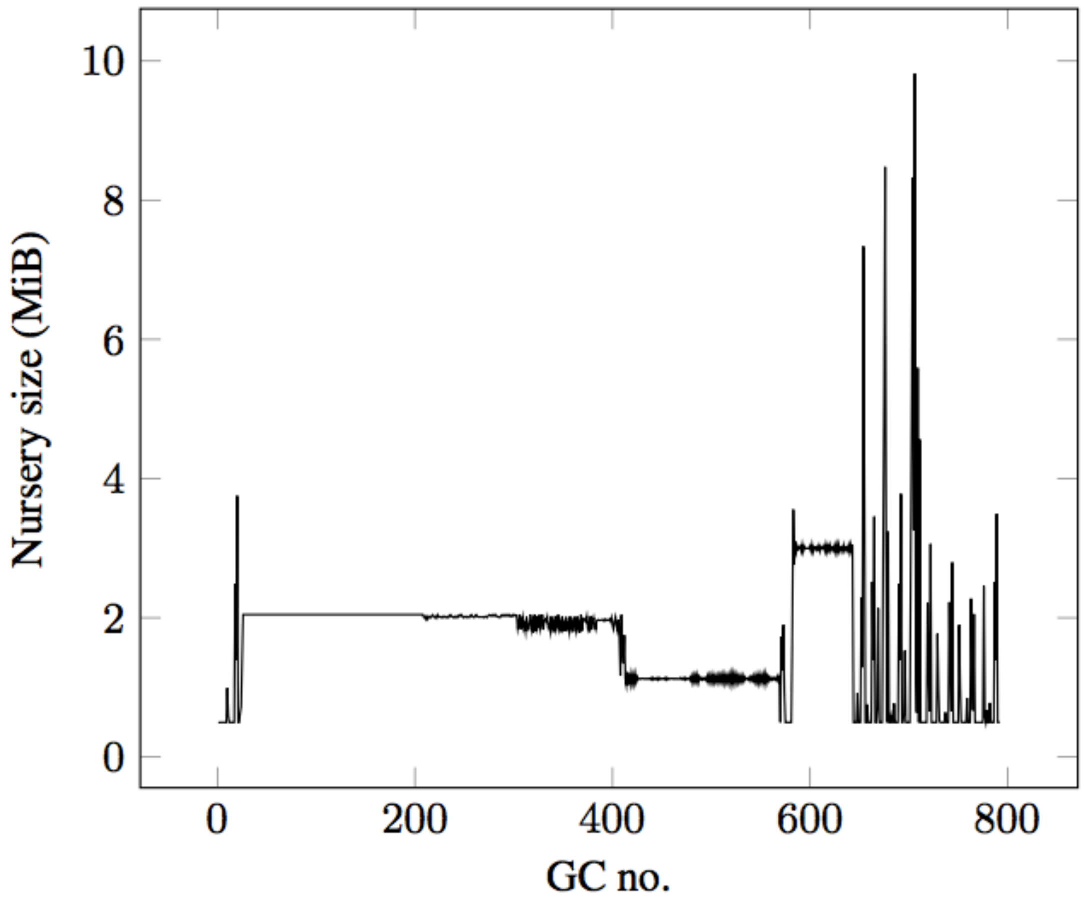
GC configuration	Speedup
-A2m	1.44
-A8m	1.69
-A64m	1.78

Speedup against default of 0.5MB fixed nursery (-A500k)

What can we conclude?

- Unlike imperative programming, a bigger nursery does not necessarily mean better performance
- In programs with irregular memory behaviour, nursery size plays a crucial role in the overall performance
- Having the same nursery size for the whole execution may be suboptimal
- In the phases of the program execution where not much data is copied, a smaller nursery size is better
- In the phases where a large amount of data is copied, go for a bigger nursery
  - **In this case garbage collection, rather than cache behaviour, is the main performance bottleneck**

Varying the Nursery Size (GHC –H)



Effect of Varying the Nursery Size

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GC configuration	Speedup
-A2m	1.44
-A8m	1.69
-A64m	1.78
-H	1.38

Speedup against default of 0.5MB fixed nursery (-A500k)

TAA Dynamic Resizing Algorithm

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- $TPBM_n$ – Time per Byte Metric
  - time taken by the n^{th} garbage collection divided by the nursery size S_n for that collection
- Target: reduce TPBM as much as possible
- Set the initial nursery size, S_1, to be the size of L2 cache
- After each garbage collection, calculate a new size S_n
  - Fast method: Half the nursery size, i.e. set $S_n = S_{n-1} / 2$
  - If fast method gives worse TPBM, i.e. if $TPBM_n > TPBM_{n-1}$, use the slow method instead
  - Slow method: Good nursery size is between S_{n-2} and S_{n-1} or between S_{n-1} and S_n – do a binary search to find the optimal value

T.A. Anderson. Optimizations in a Private Nursery-based Garbage Collector. *Proc. 2010 International Symposium on Memory Management, ISMM '10,* pages 21–30.

TAA Dynamic Resizing Algorithm (2)

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fun `fast_update()`

$S_{n-2} = S_{n-1}$

$S_{n-1} = S_n$

$TPBM_n = GCTime_n / S_n$

if $TPBM_n < TPBM_{n-1}$ **then**

$S_n = S_n / 2$

else

$S_n =$ `slow_update`(S_{n-2}, S_{n-1}, S_n)

end

return S_n

end

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TAA Dynamic Resizing Algorithm (3)

```
fun slow_update(S_{n-2}, S_{n-1}, S_n)
    if abs(S_n - S_{n-2}) < threshold then
        return S_{n-1}
    end
    S_x = (S_{n-1} + S_{n-2})/2
    [...execution with nursery size S_x ...]
    TPBM_x = GCTime_x/S_x
    if TPBM_x < TPBM_{n-1} then
        return slow_update(S_{n-2}, S_x, S_{n-1})
    else
        S_y = (S_n + S_{n-1})/2
        [...execution with nursery size S_y ...]
        TPBM_y = GCTime_y/S_y
        if TPBM_y < TPBM_{n-1} then
            return slow_update(S_{n-1}, S_y, S_n)
        else
            return slow_update(S_x, S_{n-1}, S_y)
        end
    end
```

Example of TAA

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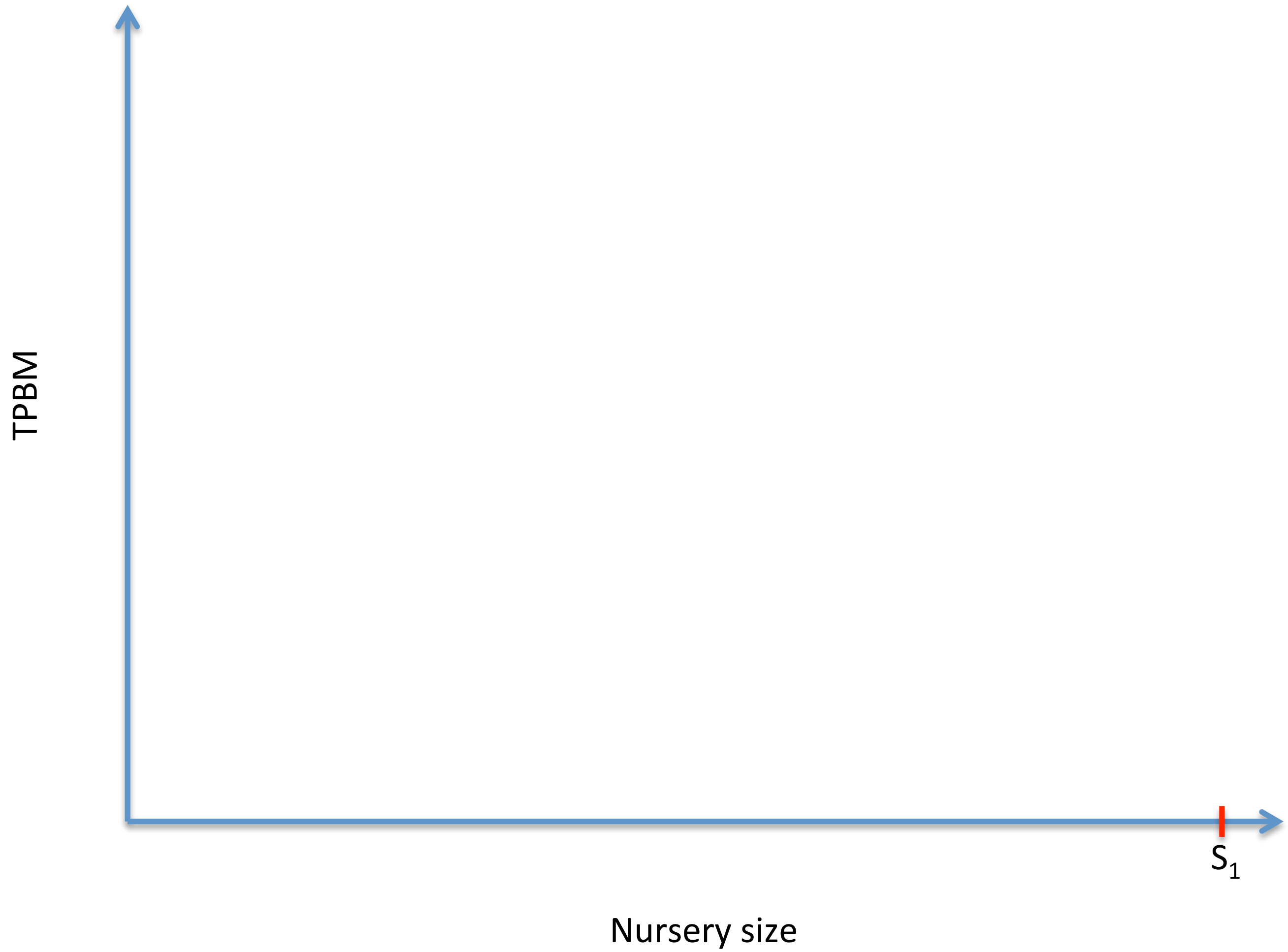

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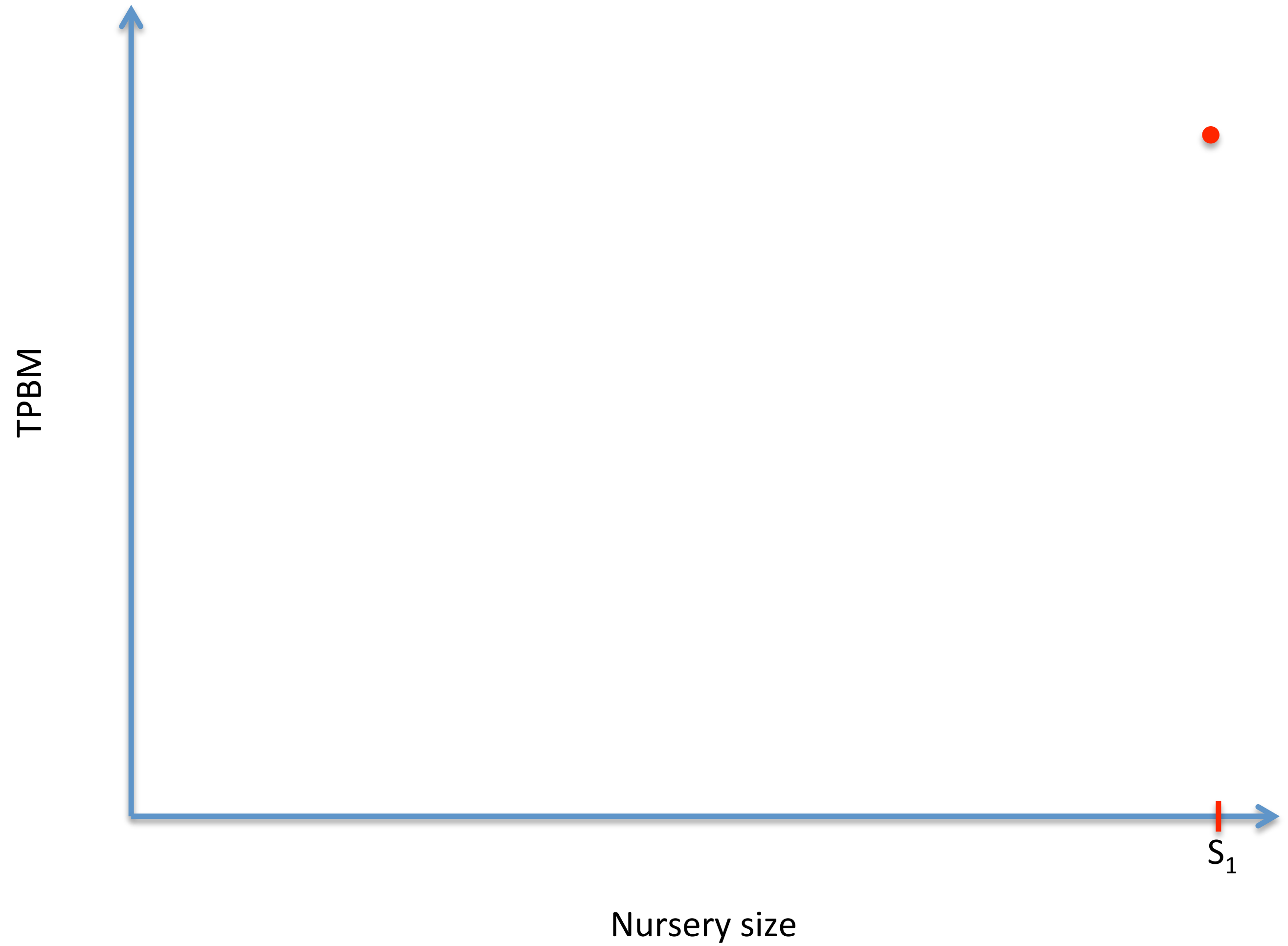
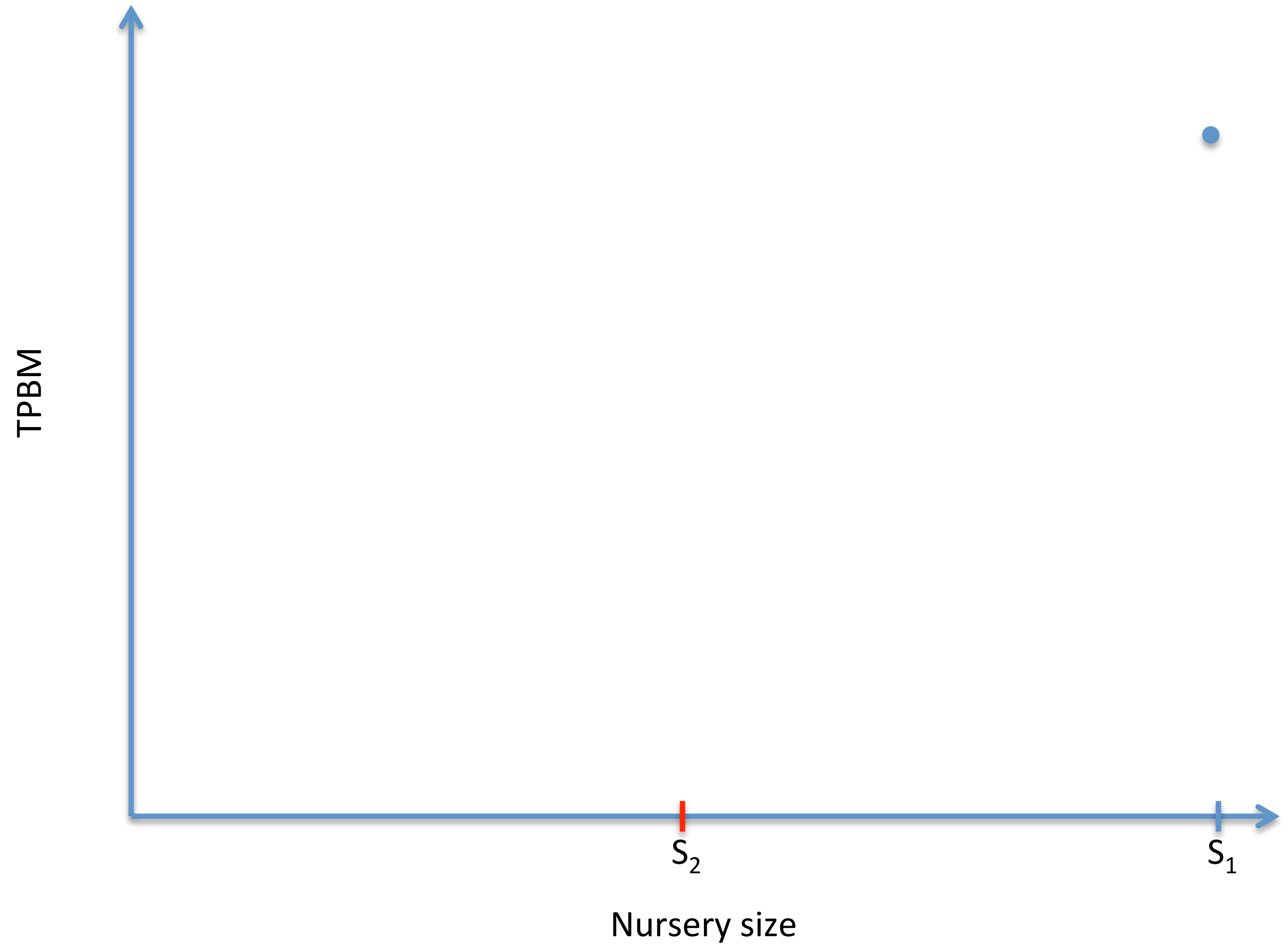
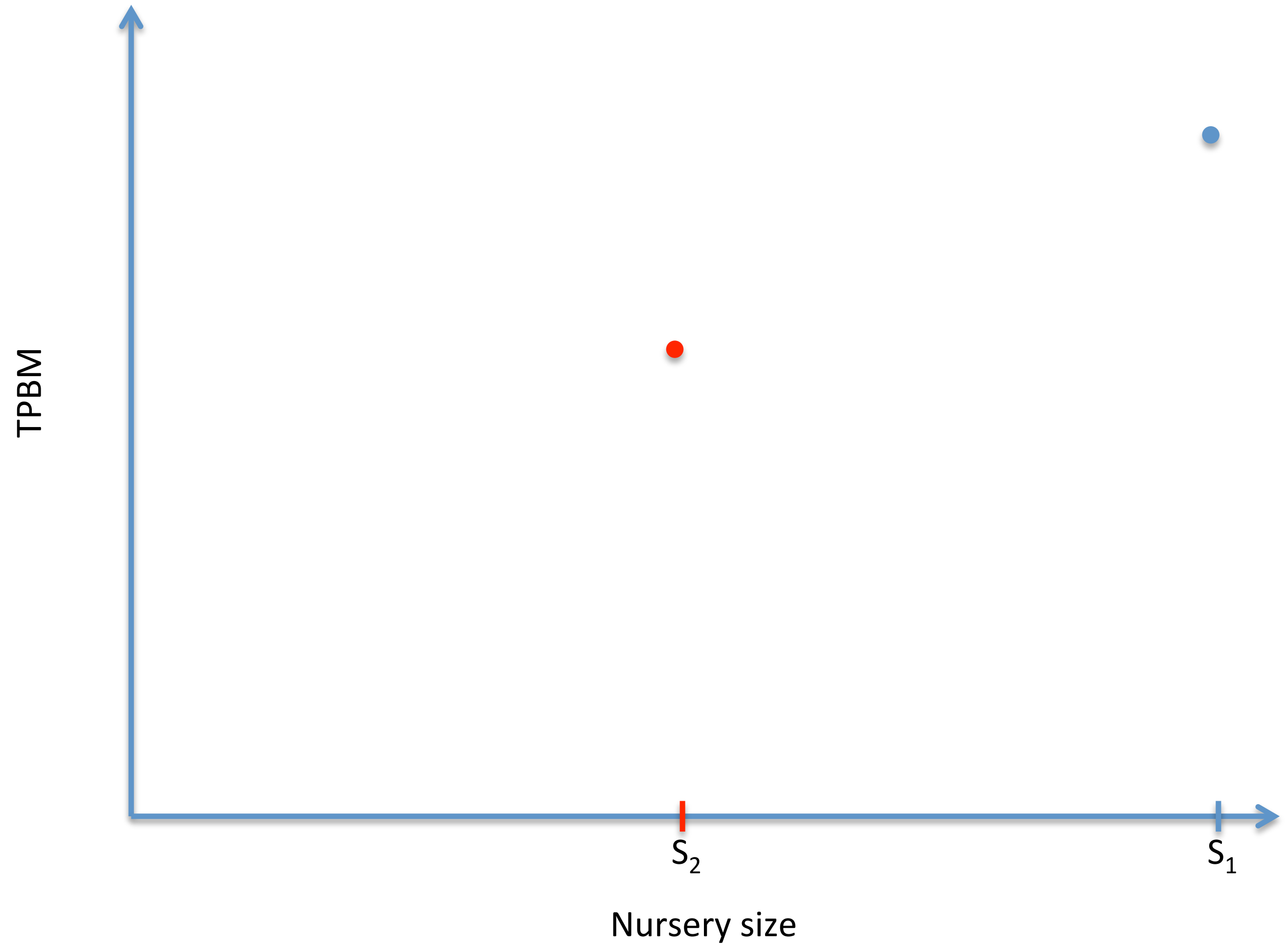
Example of TAA



Example of TAA



Example of TAA



Example of TAA

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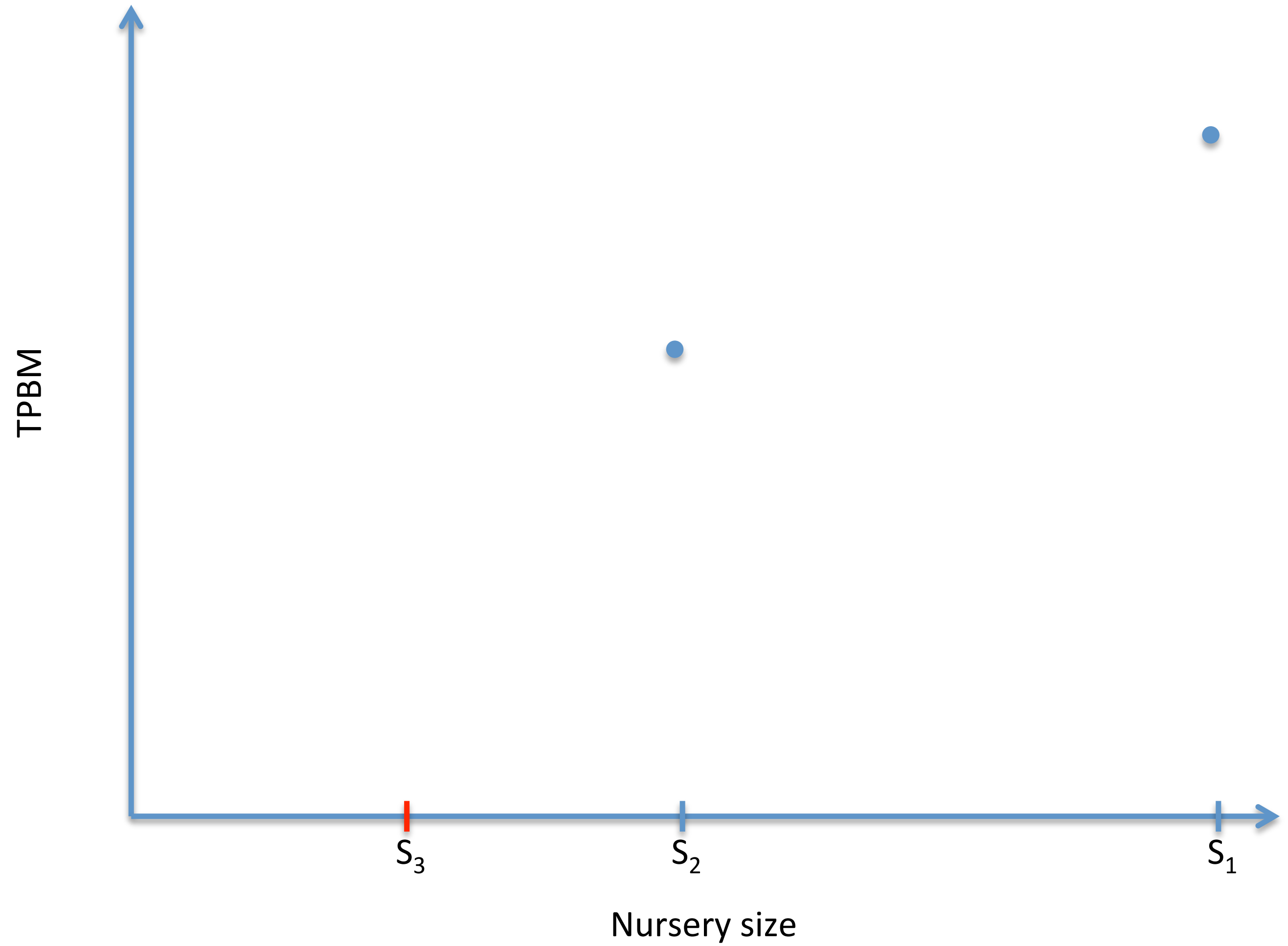
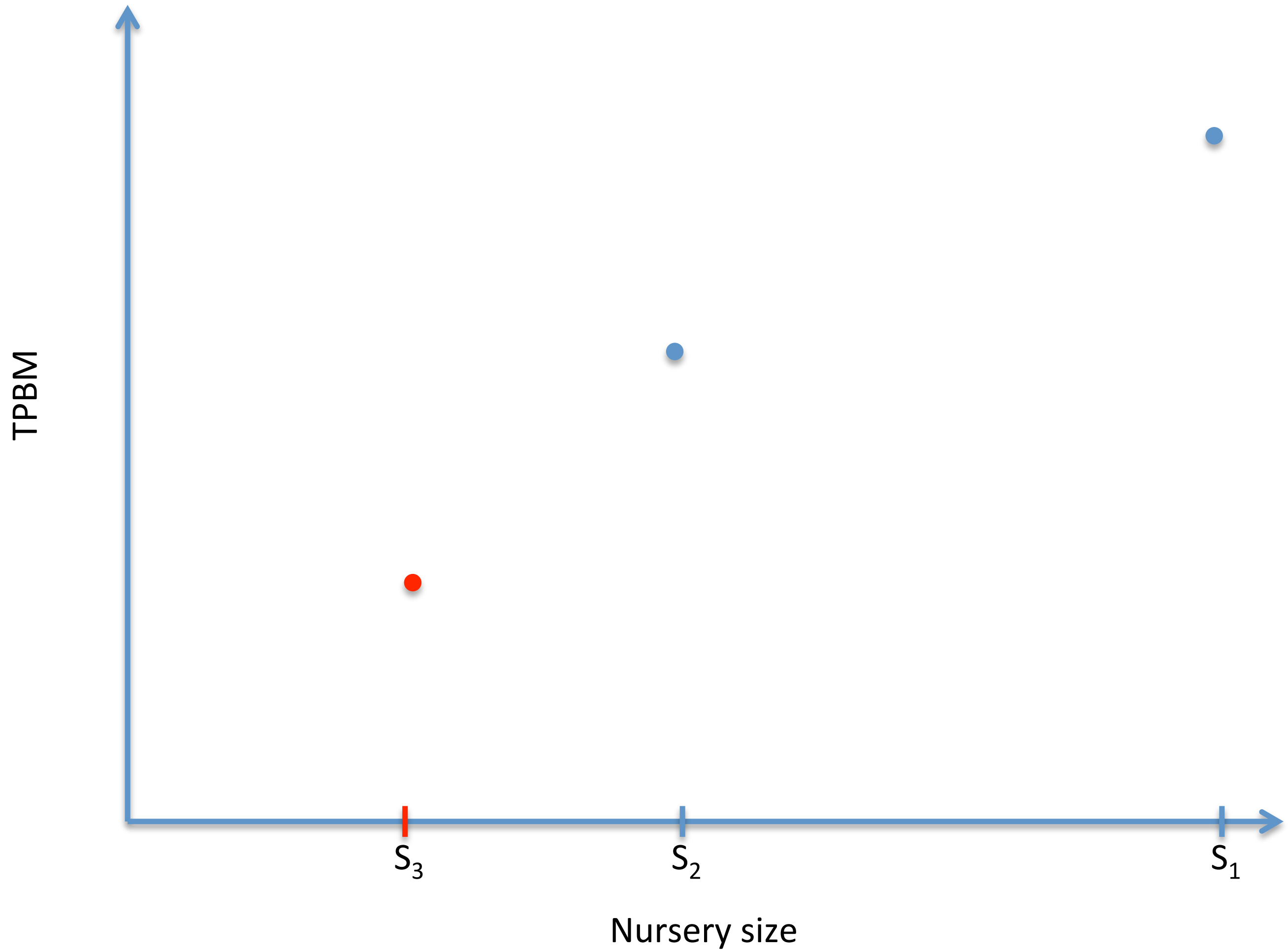
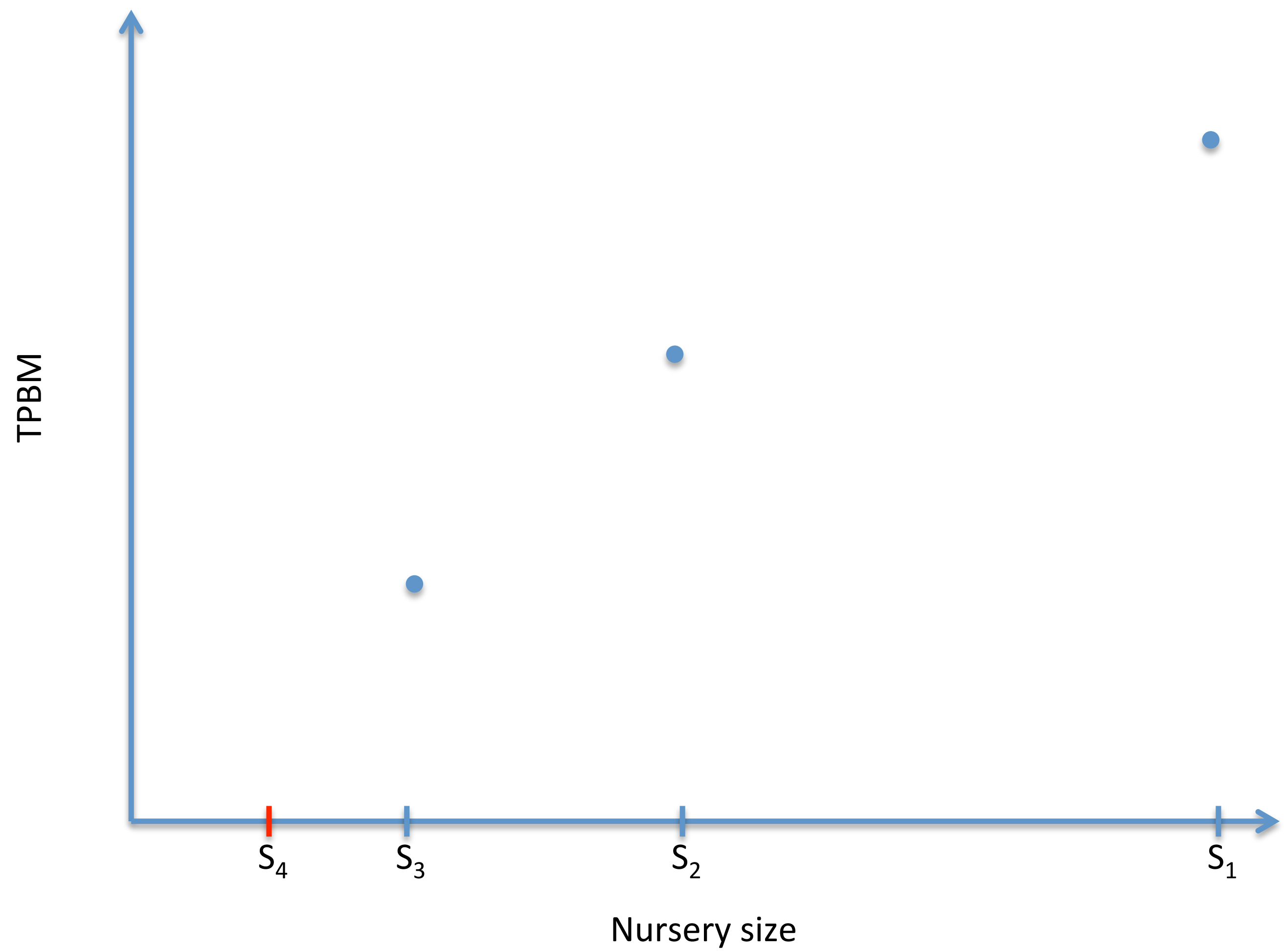


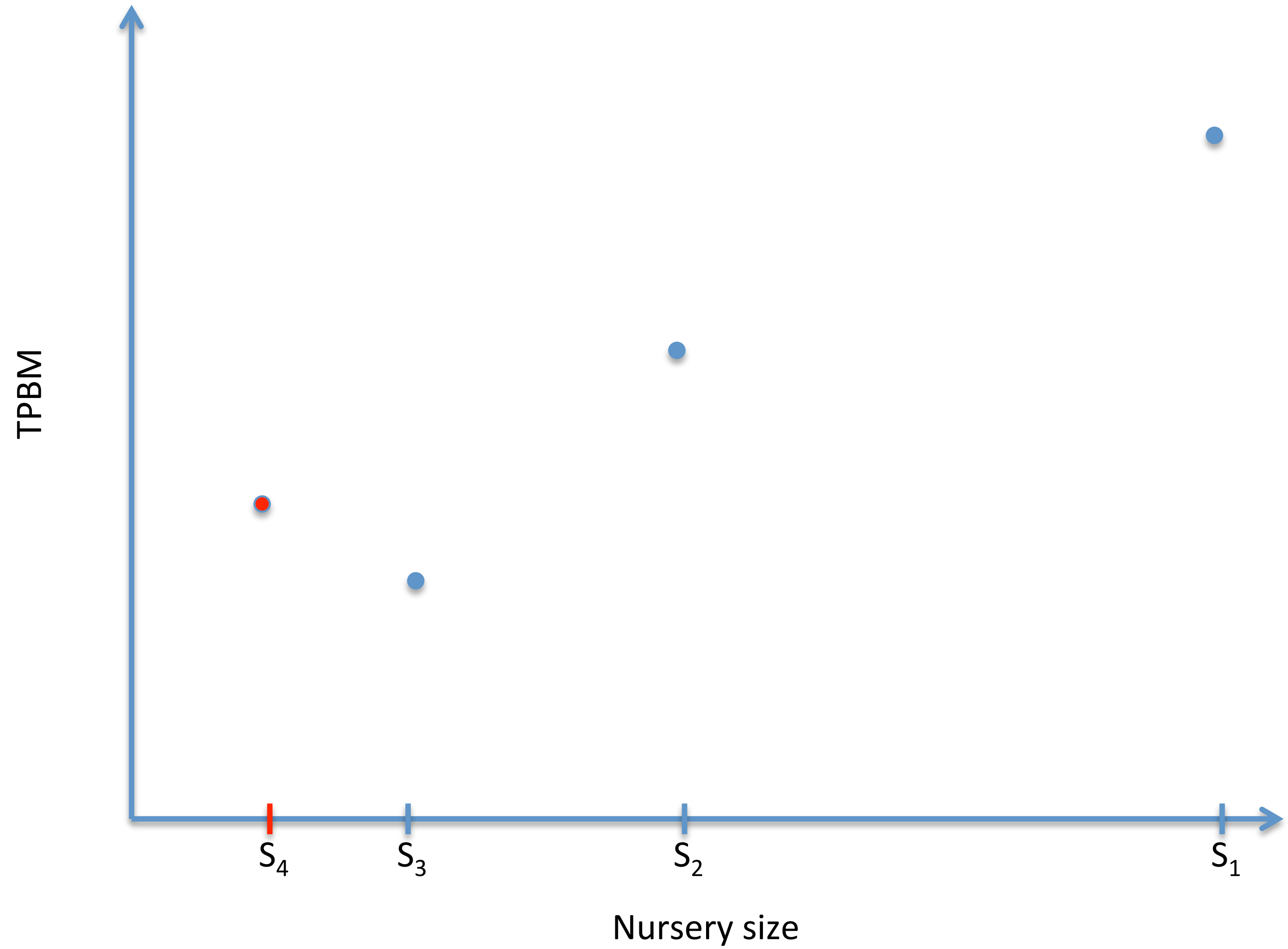
Example of TAA



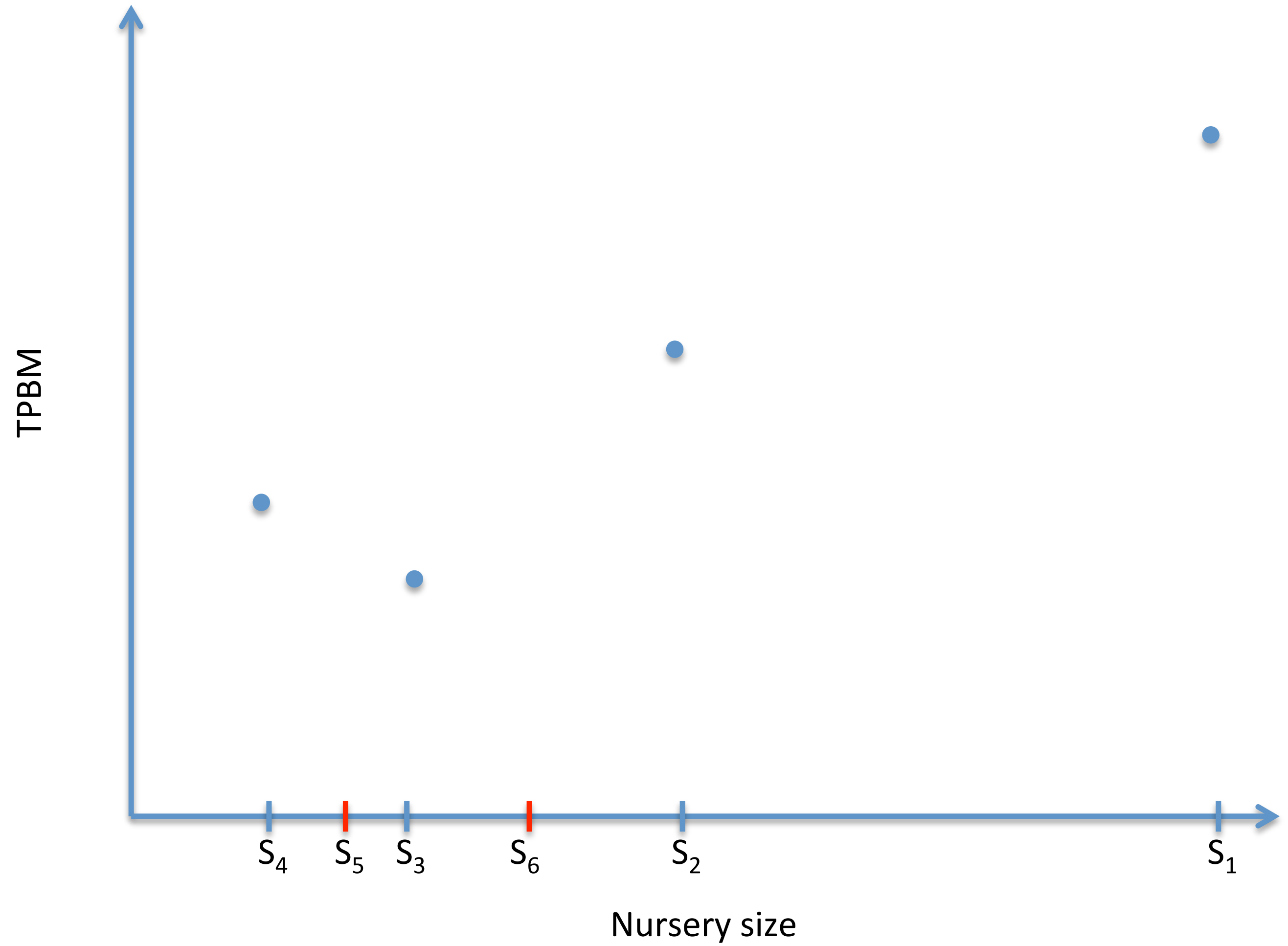
Example of TAA



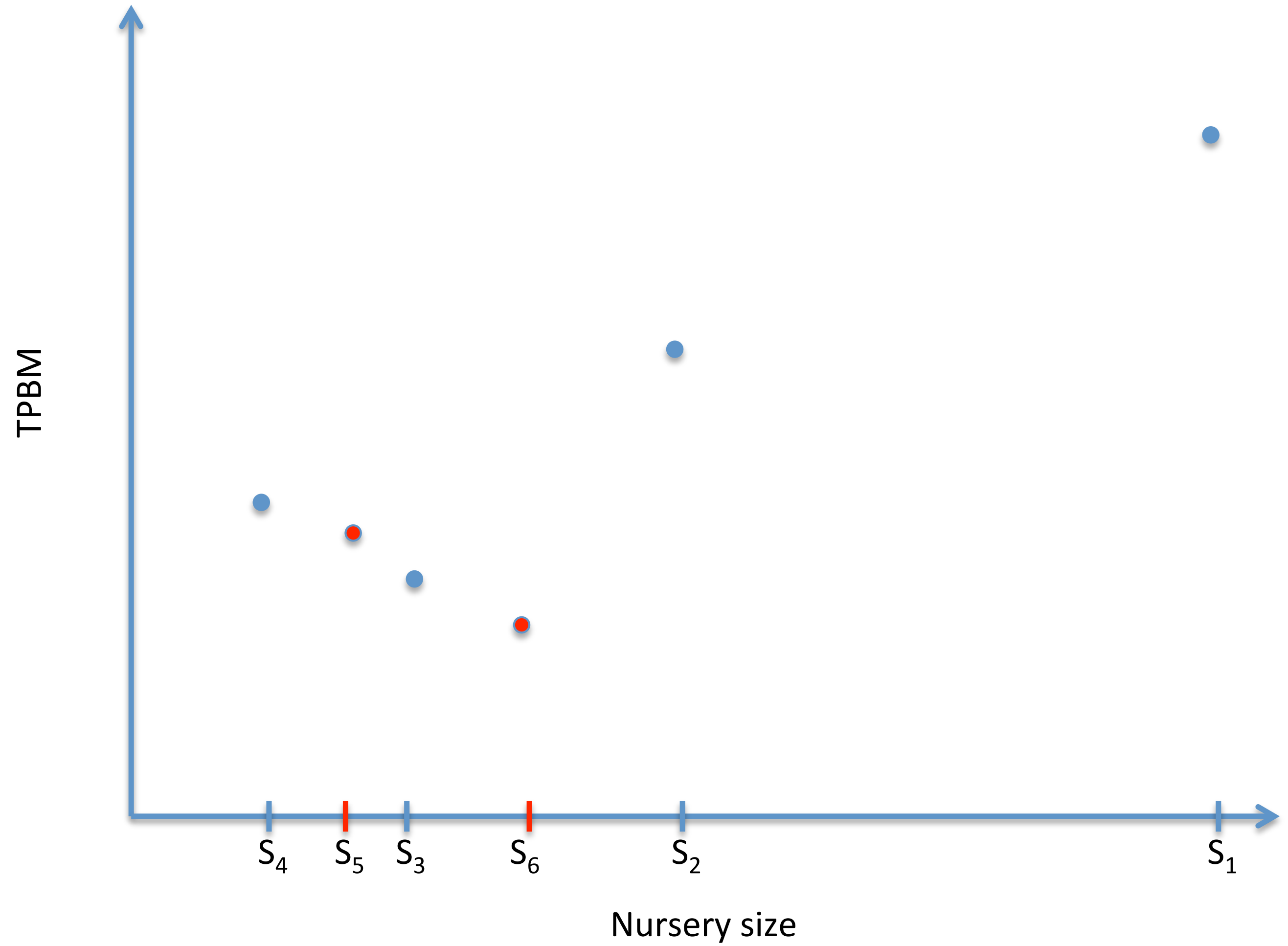
Example of TAA



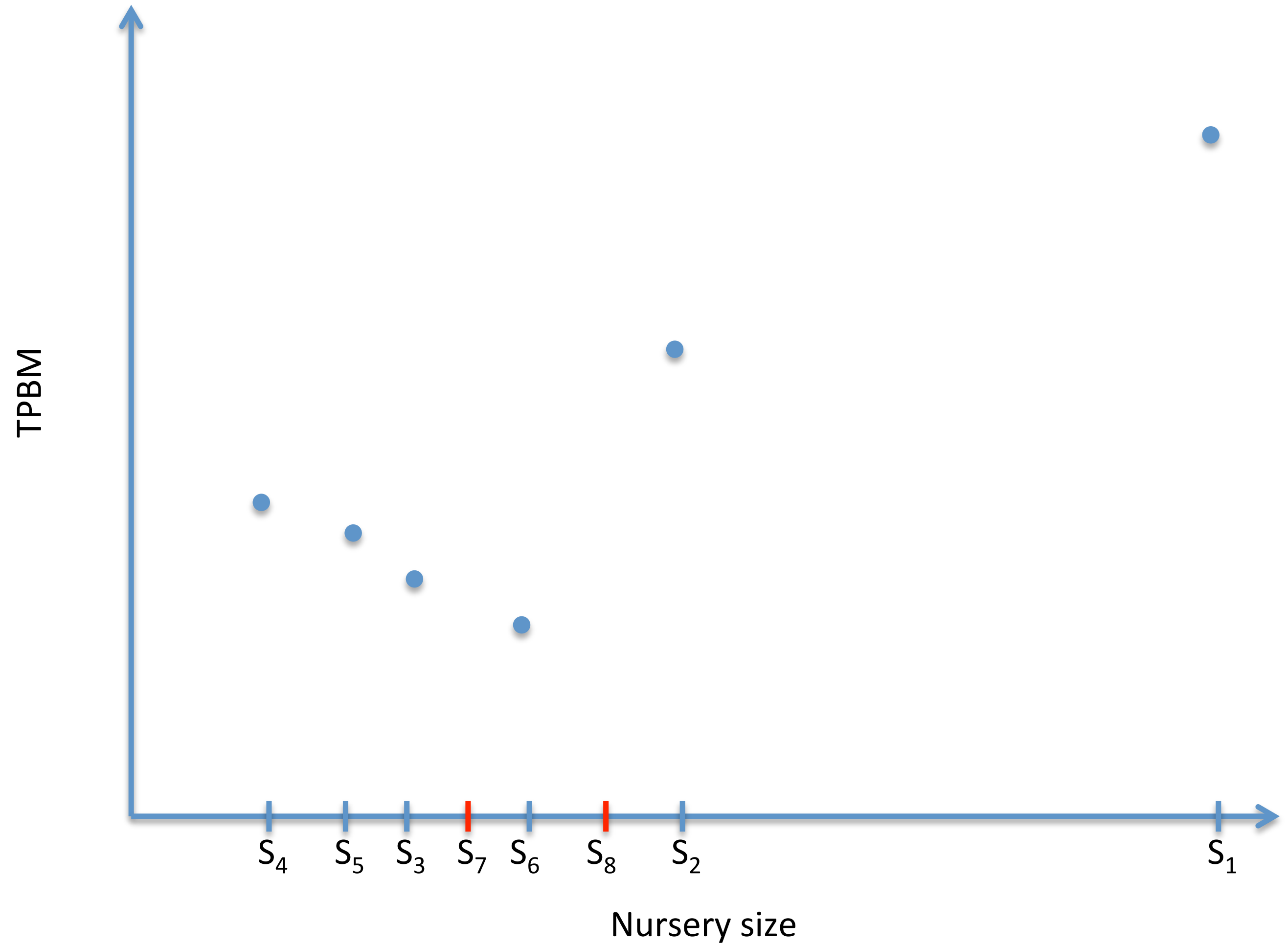
Example of TAA



Example of TAA



Example of TAA



Example of TAA

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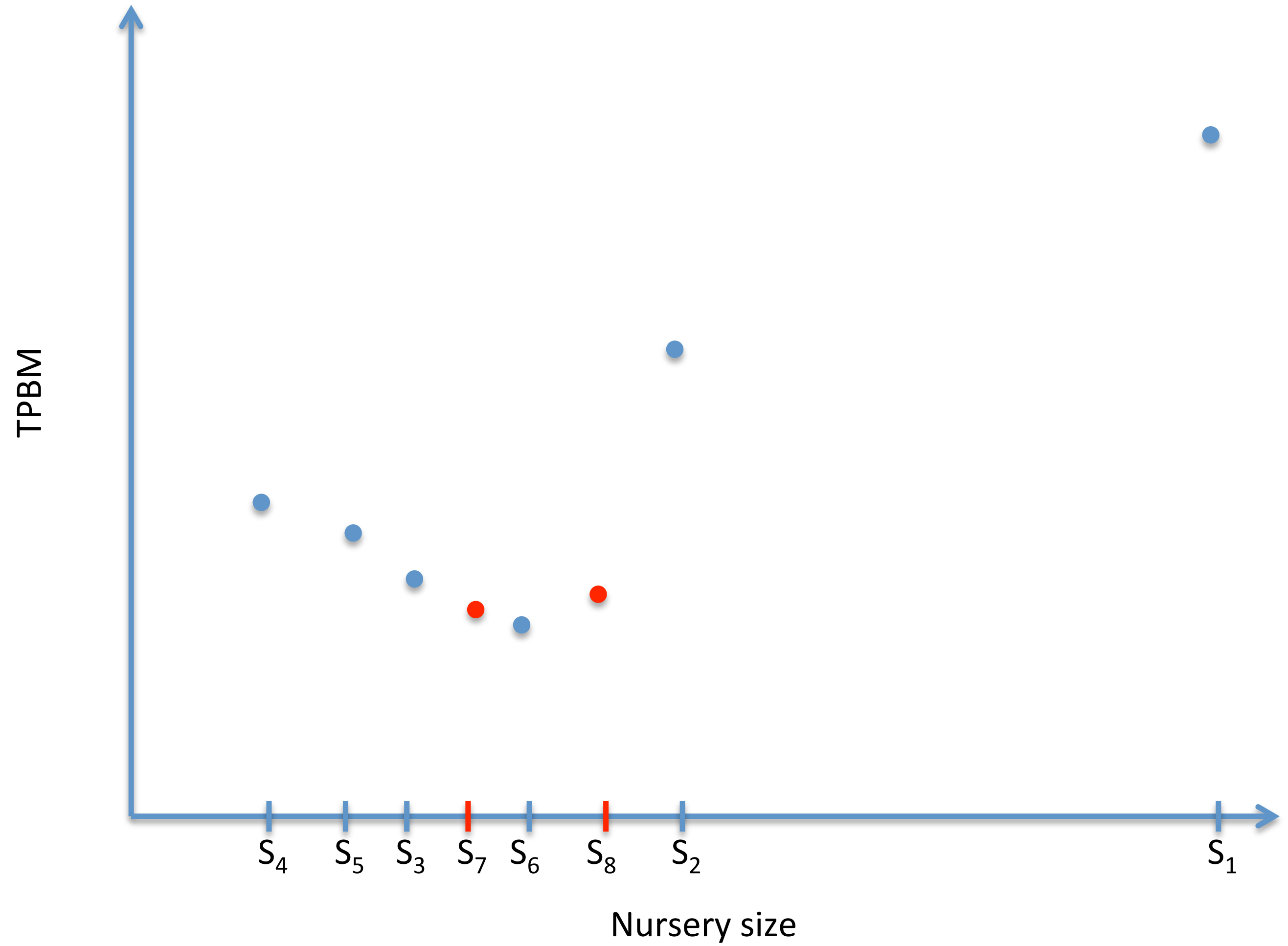
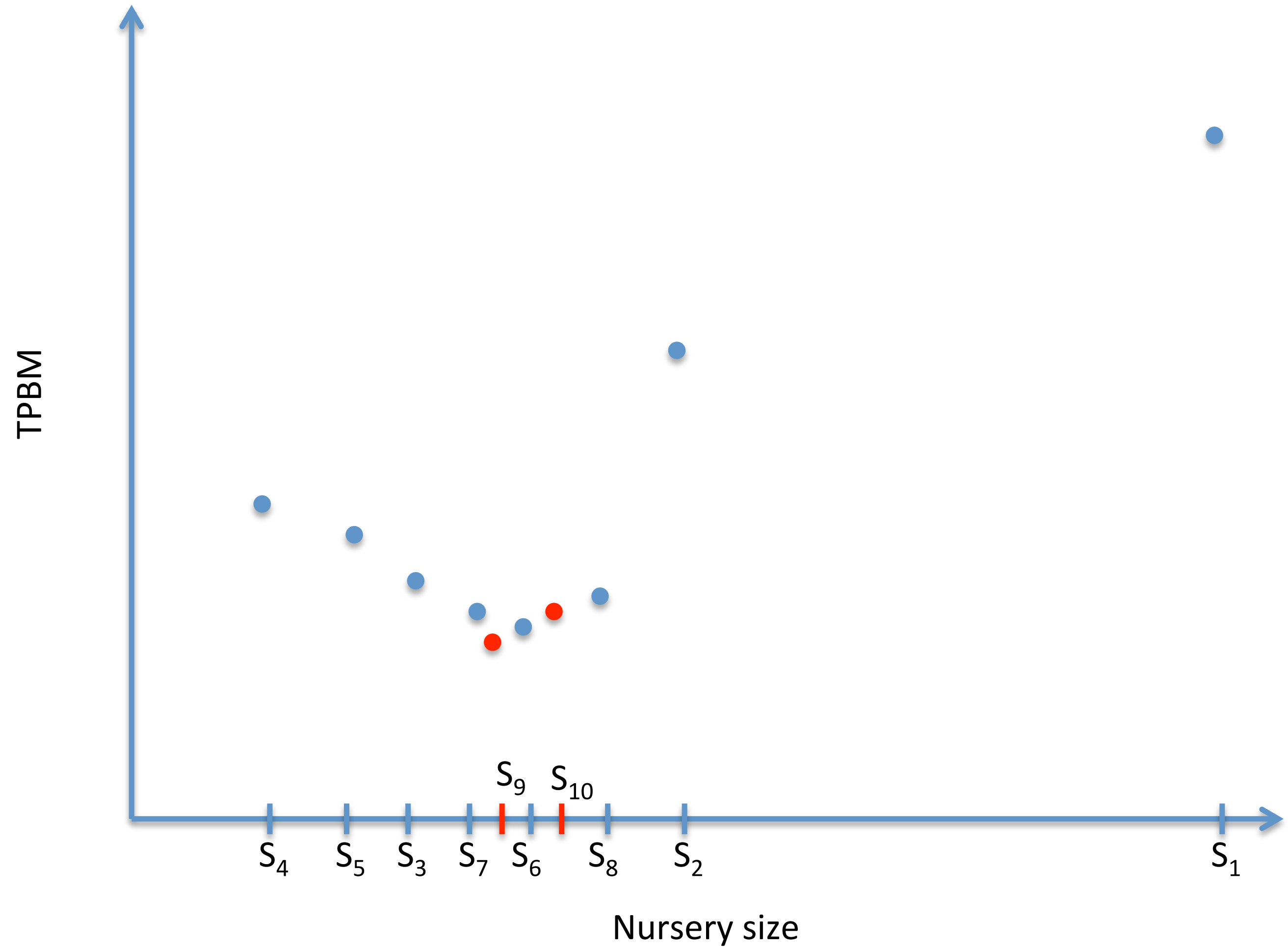


Example of TAA



Binary-trees under different algorithms (compared to GHC default)

GC configuration	Speedup
-A2m	1.44
-A8m	1.69
-A64m	1.78
-H	1.38
TAA	1.72

Speedup against default of 0.5MB fixed nursery (-A500k)

Improving TAA (TAA^{+})

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- Key assumption is that collection time is a good measure of cache locality
  - However, we have seen that this is not always the case

- Simple modification:

  Instead of just collection time, let

  TPBM = collection time *+ mutator time*

  where mutator time is time elapsed from the last collection to the current one

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Binary-trees under different algorithms (compared to GHC default)

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GC configuration	Speedup
-A2m	1.44
-A8m	1.69
-A64m	1.78
-H	1.38
TAA	1.72
TAA+	1.79

Speedup against default of 0.5MB fixed nursery (-A500k)

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Drawbacks of TAA and TAA+

- Reacts to changes in program memory behaviour by *guessing* whether to increase or decrease nursery
- Reacts *after* these changes happen
- Can be very slow in responding to changes
  - Nursery size may have to be adjusted several times in order to get the right value

Copying-based algorithm (SLR)

- Use the amount of copied data in each collection (in relation to the nursery size) to estimate the performance

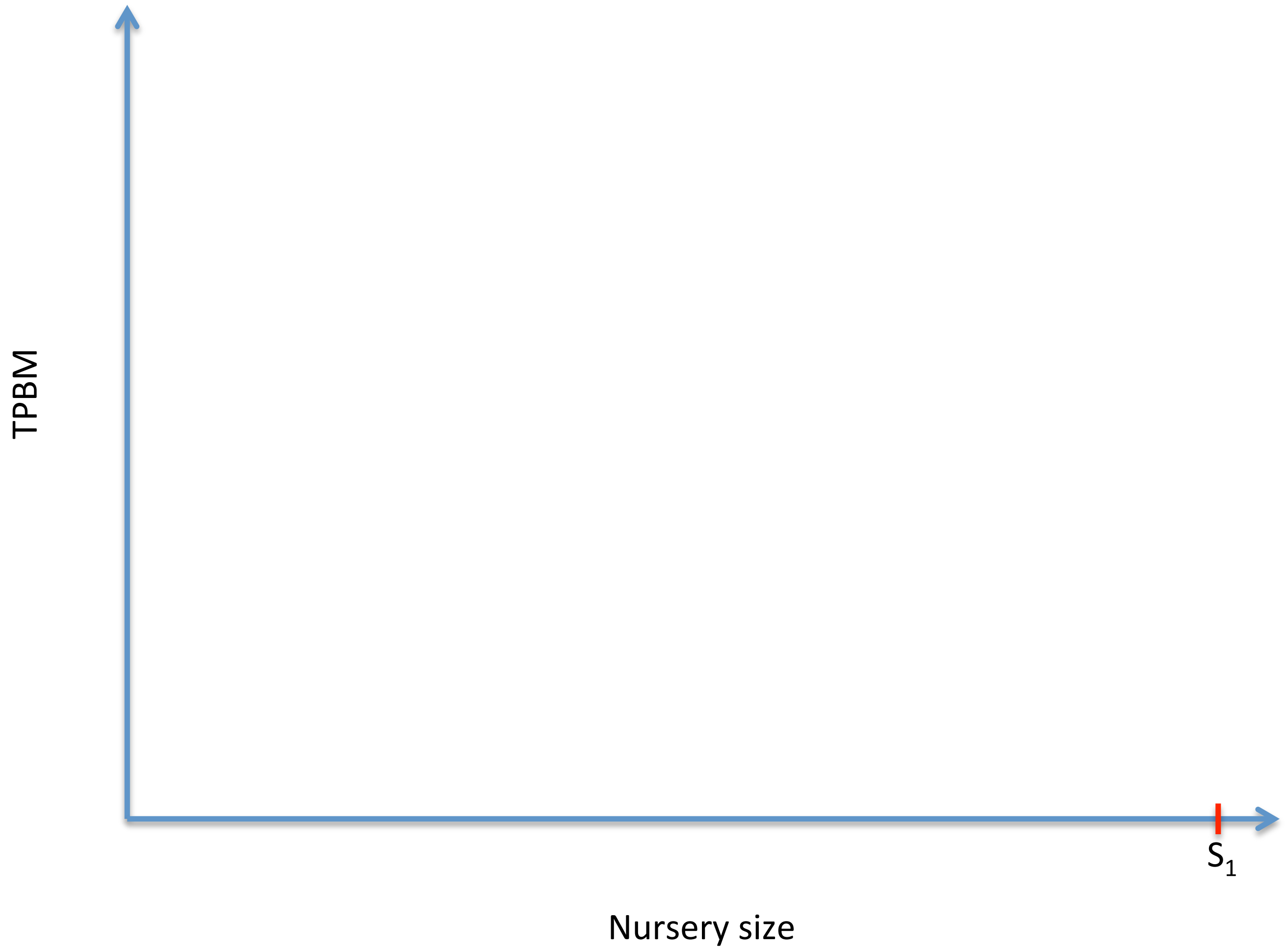
- Objective: find the *optimum* ratio of nursery size to live data, and then use it to calculate the nursery size
  - Nursery Size to Live Data Ratio (*SLR*)

- Starting with the initial *SLR*, modify it slightly after each garbage collection (and update the nursery size appropriately), until we find the right value

SLR algorithm

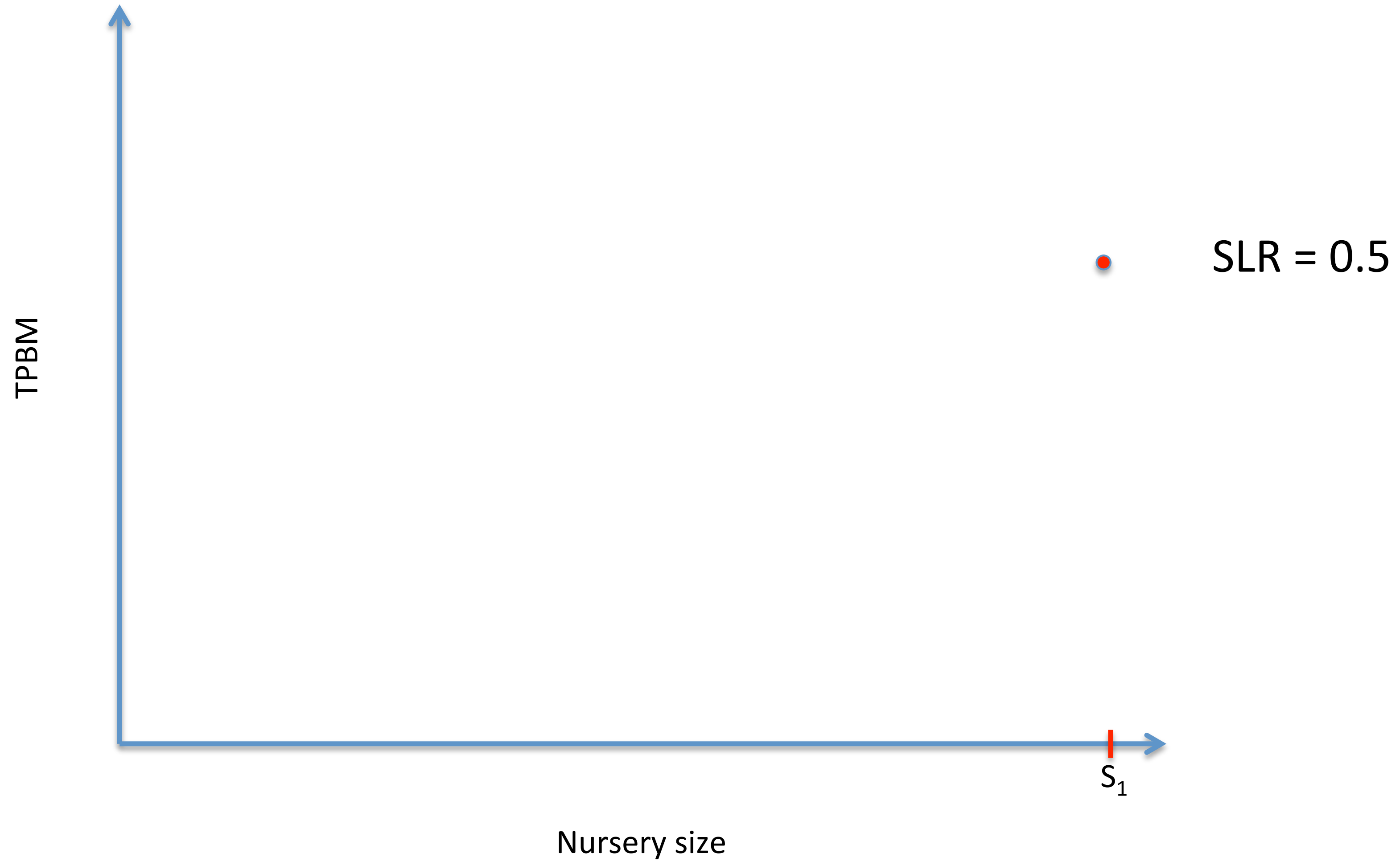
```
fun resize()
    TPBM_{n-1} = TPBM_n
    TPBM_n = (MUTTime_n + GCTime_n)/S_n
    if abs(TPBM_n - TPBM_{n-1}) < threshold then
        update_factor = update_factor_0 // reset value
        SLR_n = SLR_{n-1}
    else
        // if performance is worse, reverse
            update direction
        if TPBM_{n-1} > TPBM_n then
            update_factor = -0.9 × update_factor
        end
        SLR_n = SLR_{n-1} × (1 + update_factor)
    end
    return SLR_n × copied_n
end
```

Example of SLR

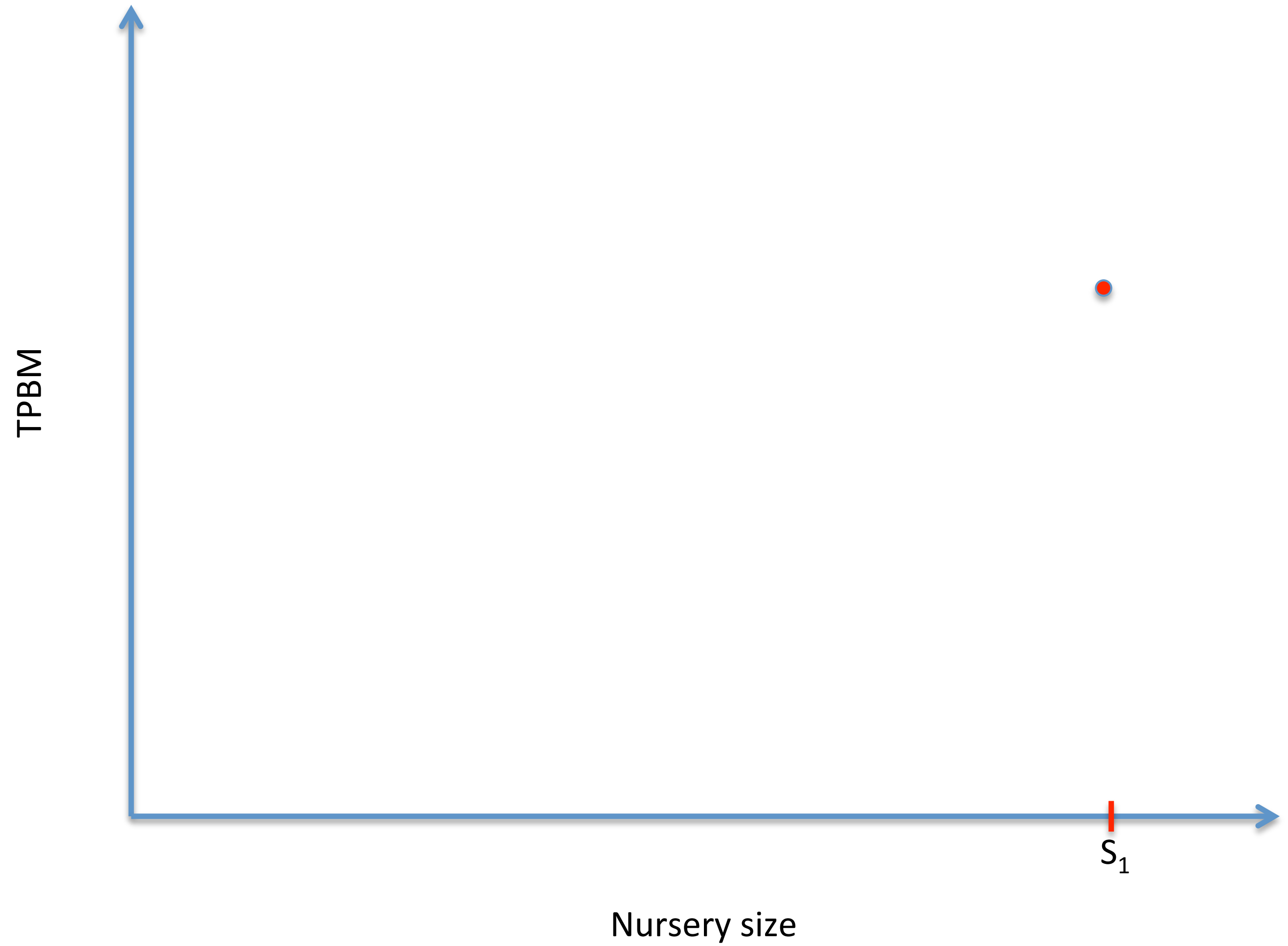


SLR = 0.5

Example of SLR



Example of SLR



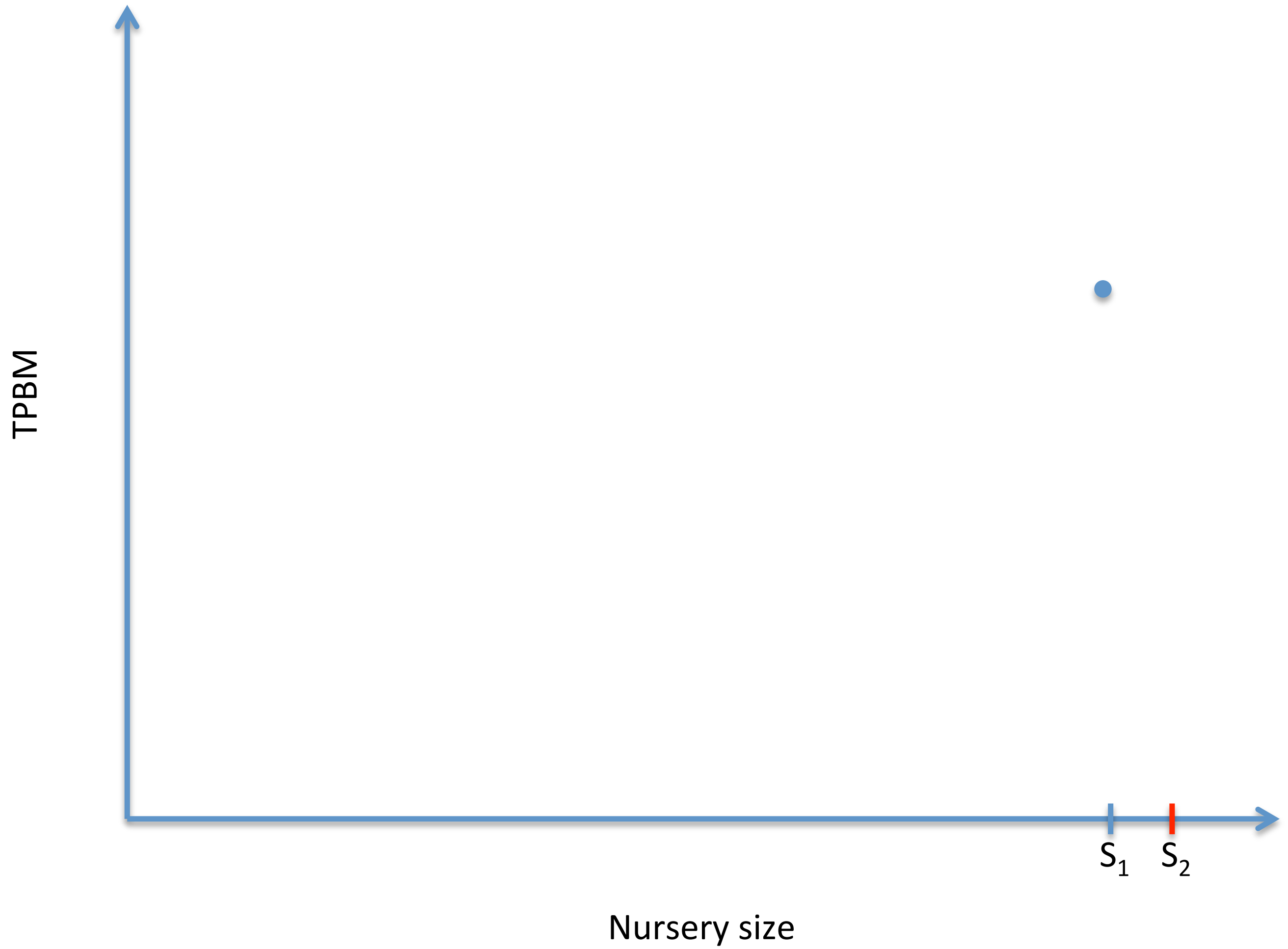
SLR = 0.5

S1 = 1MB

SLR = 0.45, C = 0.5MB

S2 = 1.11MB

Example of SLR



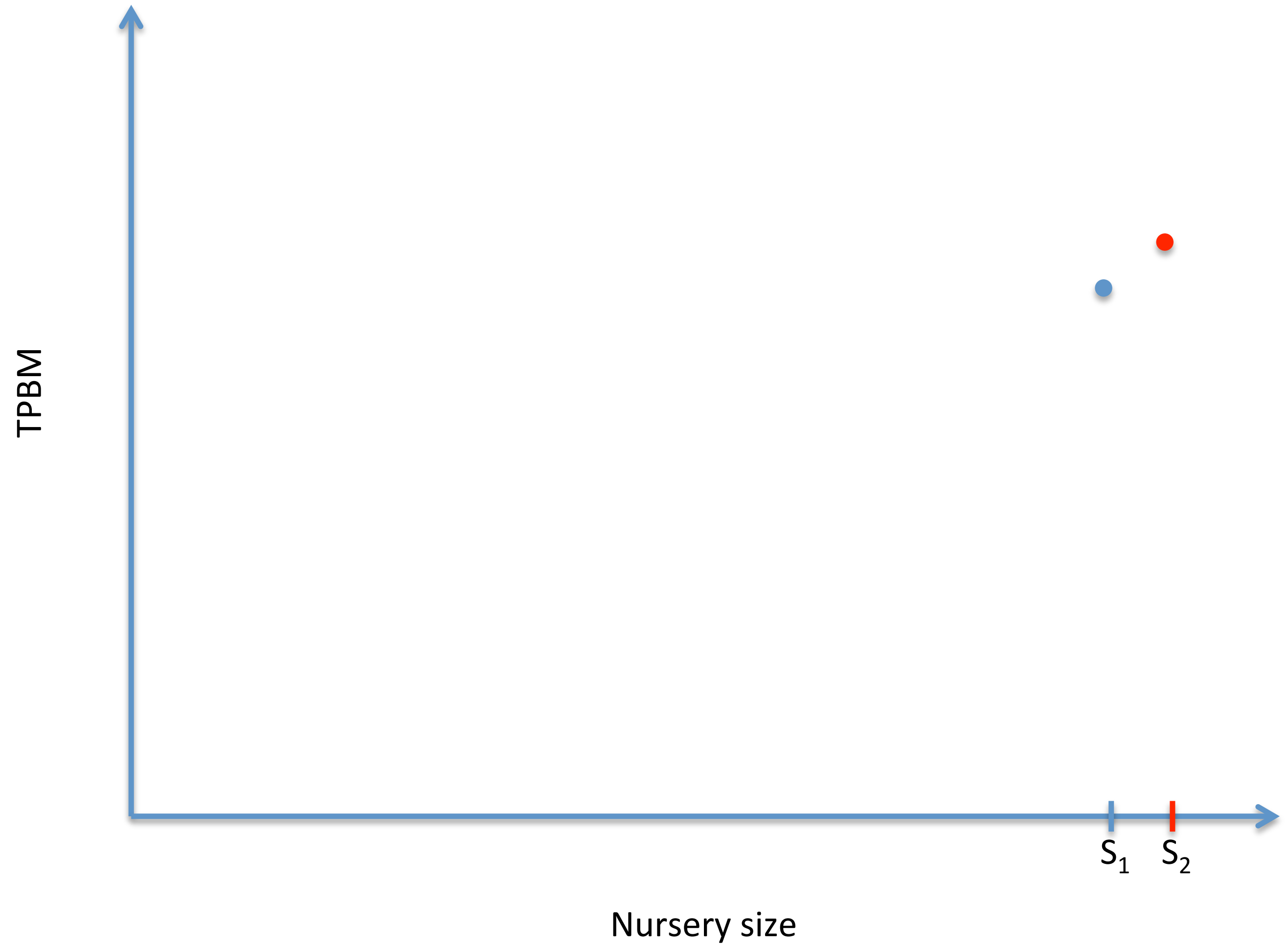
SLR = 0.5

S1 = 1MB

SLR = 0.45, C = 0.5MB

S2 = 1.11MB

Example of SLR



SLR = 0.5

S1 = 1MB

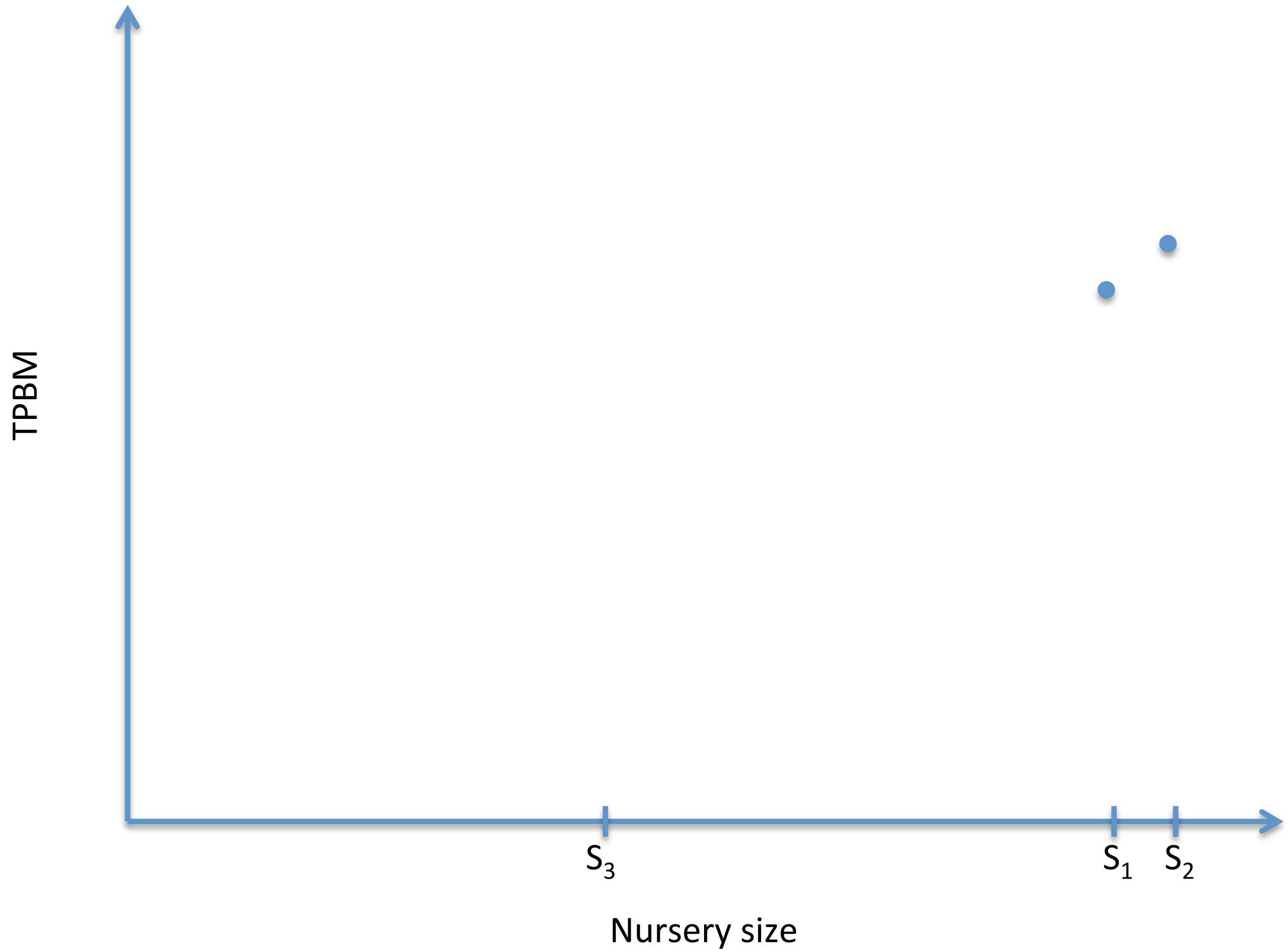
SLR = 0.45, C = 0.5MB

S2 = 1.11MB

SLR = 0.55, C = 0.3MB

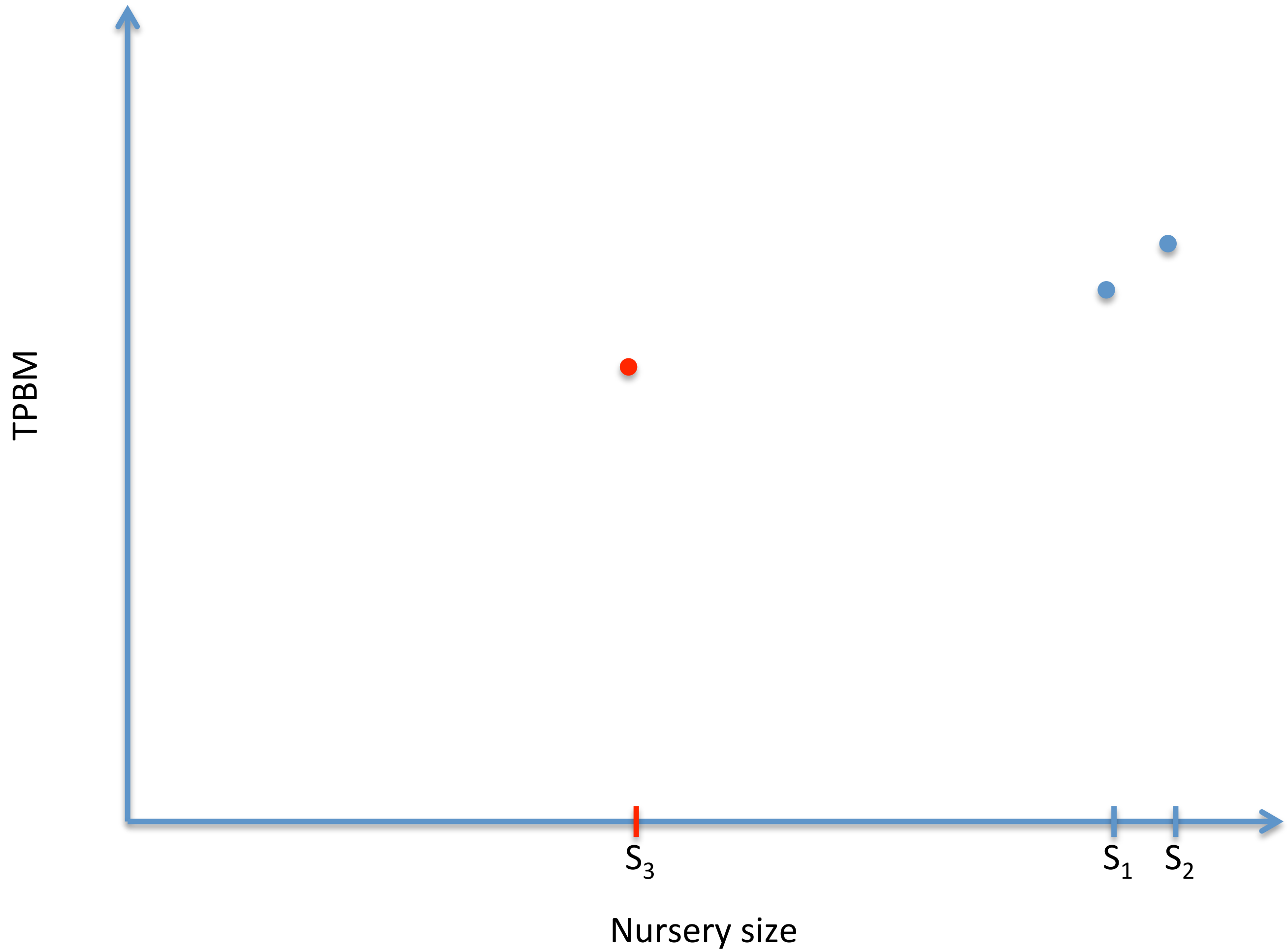
S3 = 550k

Example of SLR



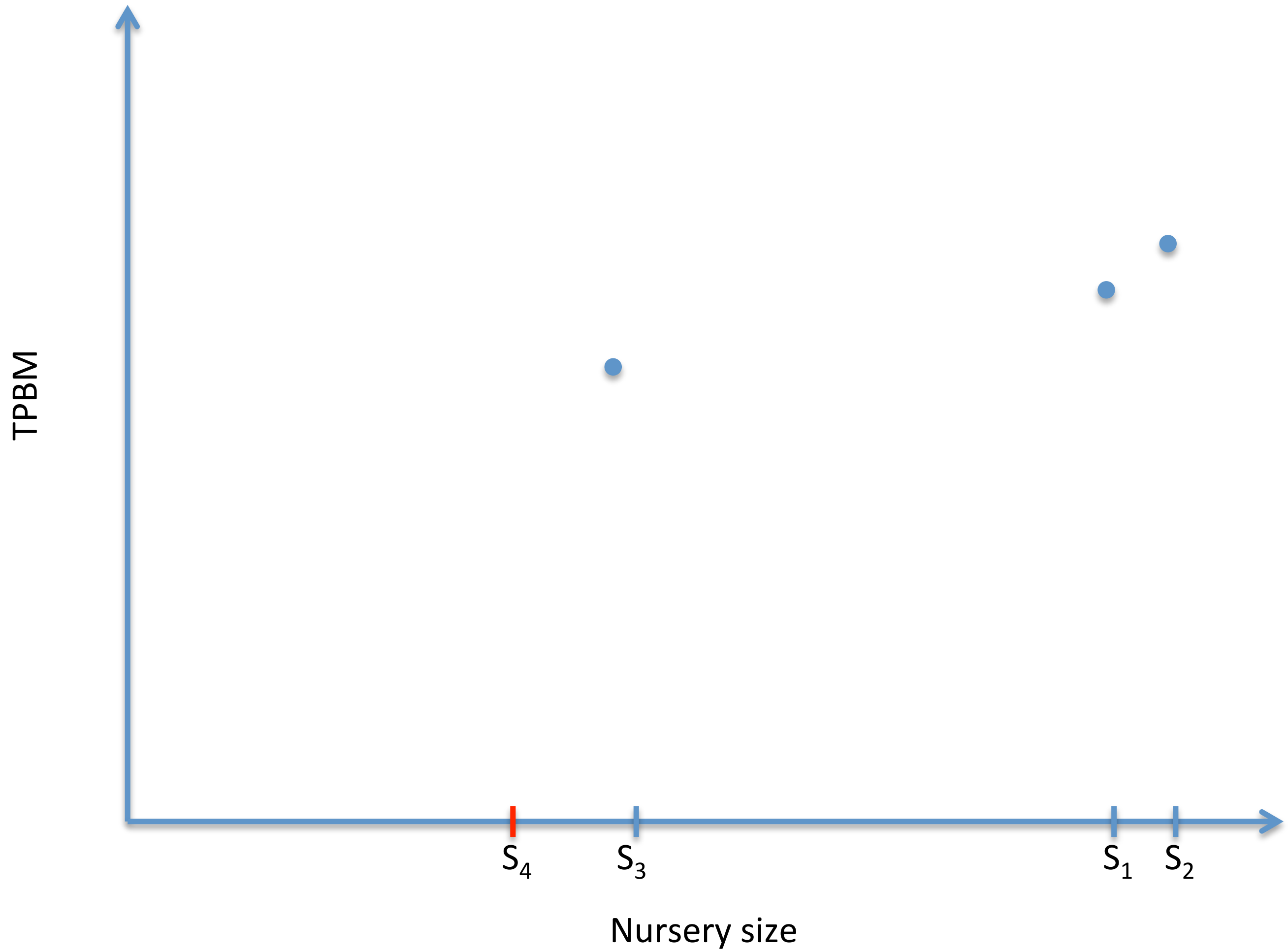
SLR = 0.5
S1 = 1MB
SLR = 0.45, C = 0.5MB
S2 = 1.11MB
SLR = 0.55, C = 0.3MB
S3 = 550k

Example of SLR



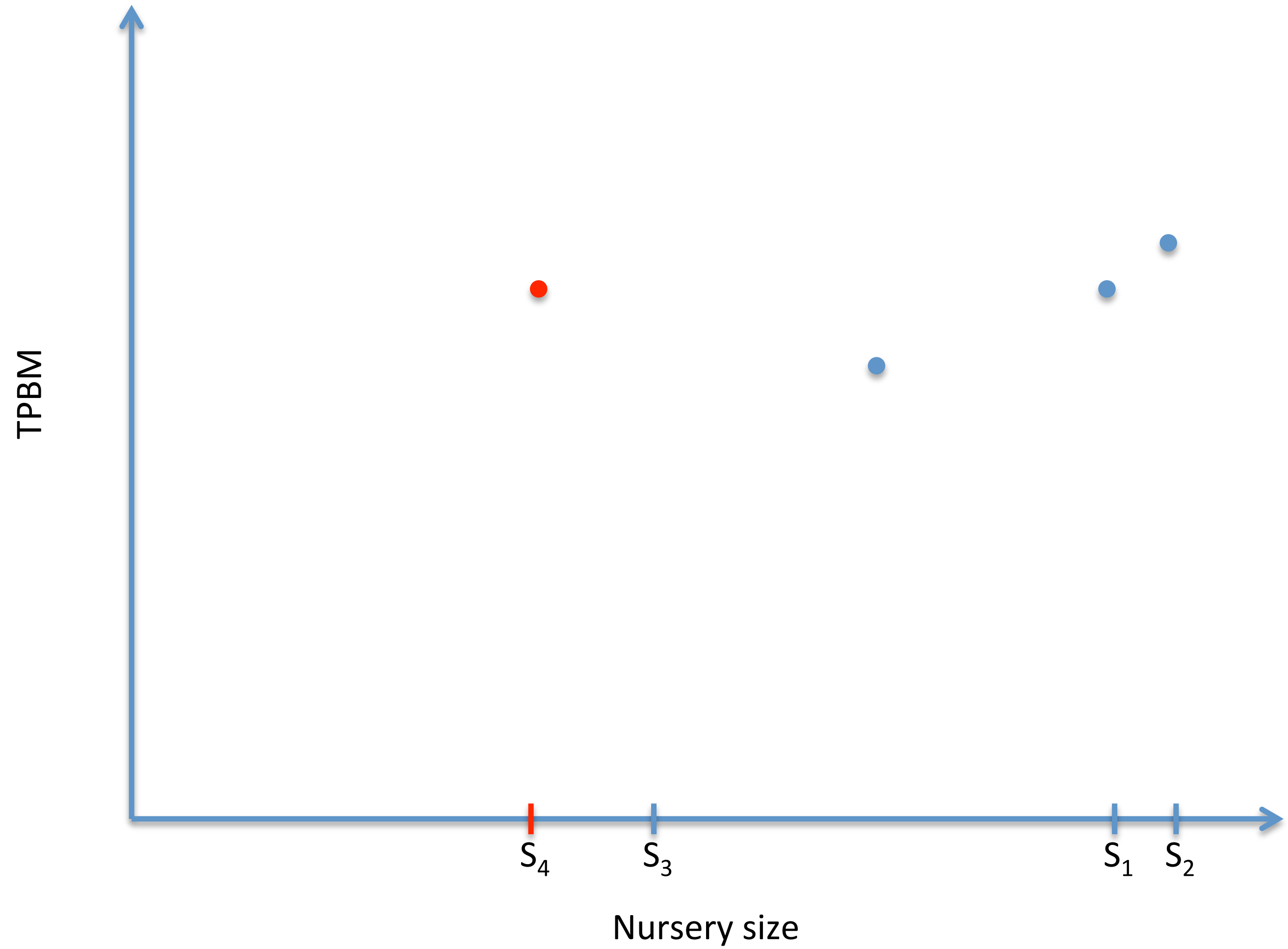
SLR = 0.5
S1 = 1MB
SLR = 0.45, C = 0.5MB
S2 = 1.11MB
SLR = 0.55, C = 0.3MB
S3 = 550k
SLR = 0.60, C = 0.3MB
S4 = 500k

Example of SLR



SLR = 0.5
  S1 = 1MB
SLR = 0.45, C = 0.5MB
  S2 = 1.11MB
SLR = 0.55, C = 0.3MB
  S3 = 550k
SLR = 0.60, C = 0.3MB
  S4 = 500k

Example of SLR



SLR = 0.5

S1 = 1MB

SLR = 0.45, C = 0.5MB

S2 = 1.11MB

SLR = 0.55, C = 0.3MB

S3 = 550k

SLR = 0.60, C = 0.3MB

S4 = 500k

SLR = 0.57, C = 0.2MB

S5 = 350k

Improvement with SLA

GC configuration	Speedup
-A2m	1.44
-A8m	1.69
-A64m	1.78
-H	1.38
TAA	1.72
TAA^+	1.79
SLR	1.96

Speedup against default of 0.5MB fixed nursery (-A500k)

Evaluation of TAA, TAA^+ and SLR

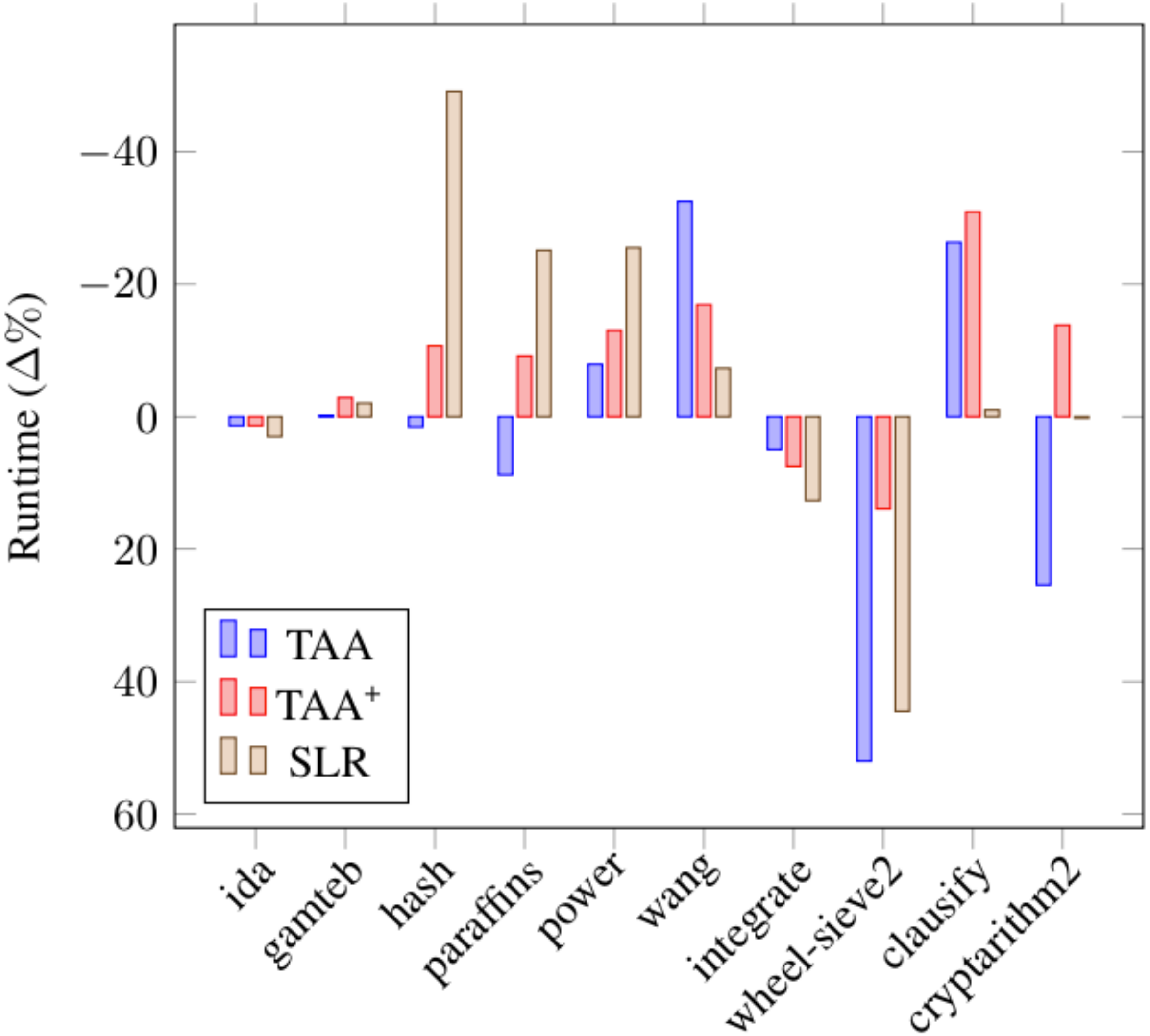
Evaluated on the *nofib* benchmark suite of 63 Haskell benchmarks (real, spectral, imaginary)

Performance	TAA	TAA^+	SLR
unaffected	58.0	51.6	61.3
positive	19.4	30.6	33.9
negative	22.6	17.7	4.8

SLR is the best default option

- Average improvement in runtime of 10%
- The best improvement 88.5%
- Worst case gives slowdown of 44.5% (in just one example)
  - compared with 52.0% for TAA, 28.2% for TAA^+

Main Affected Benchmarks



SLR v. TAA

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- Both can suffer from “initial slowdown”, where nursery size is incorrectly guessed at the beginning
- Relevant information (TPBM) calculated *after* collections, and cannot be obtained *beforehand*
- SLR adapts better to memory usage changes, since nursery size is always modified in proportion to the amount of copied data

Conclusions

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- Nursery size can have a significant impact on the performance of functional programs
- We have established a relation between nursery size and the execution time of a program
  - The interplay between cache locality and the amount of data copied during the collection
- Introduced two novel algorithms for dynamic tuning of the nursery size: TAA^{+} and SLR
  - SLR gives the best overall performance, and is a sensible default for GHC

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Future Work

- Quantify memory irregularity and relate it to improvements in execution time
- Study influence of other factors on GC performance and include these in more sophisticated
  - e.g. amount of data accessed
- Investigate TAA+ and SLR for imperative languages
  - e.g. C++, Java
- Dynamic nursery resizing algorithms for parallel programs

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