Rubyにおける ライトバリアのないオブジェクトを考慮した 世代別インクリメンタルGCの実装

笹田 耕一, 松本 行弘

(Heroku, Inc.)

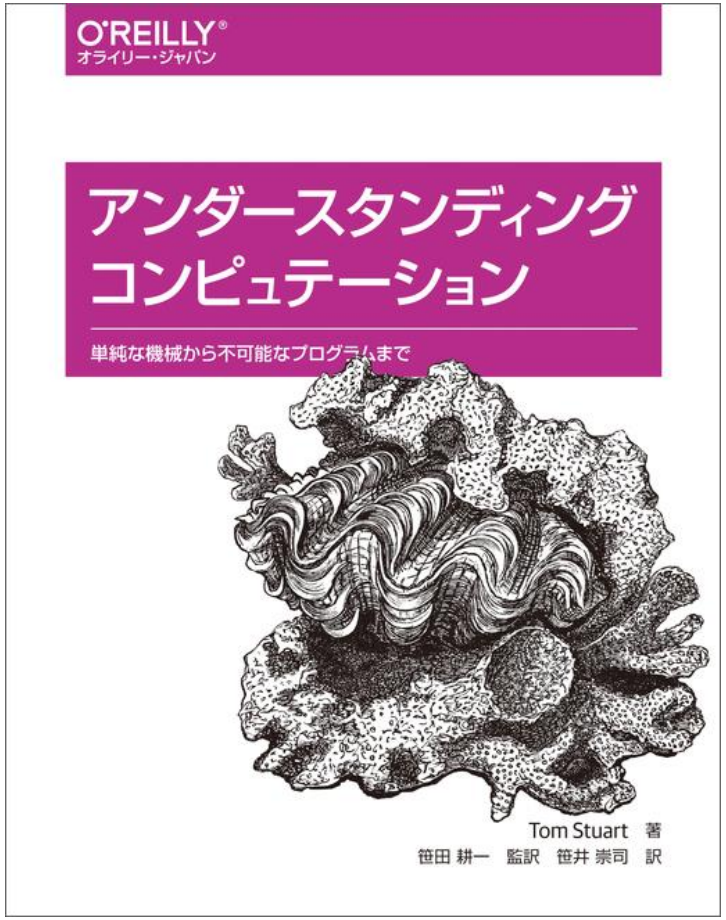
この発表を3行でまとめると

- Ruby処理系にはライトバリア（WB）が入っていないし、実装大変
- 世代別GC、インクリメンタルGCはWBが無いと実装できない
- 完璧にWBが入って無くても出来るアルゴリズムを考えました

Programming language Ruby

- Object oriented programming language Ruby
- Ruby is widely used in world-wide.

Rubyが使われている例



- アンダースタンディング コンピュテーション（オライリー）
- Tom Stuart著、笹田 耕一監訳、笹井 崇司訳
- Ruby で意味論、オートマトン、チューリング機械、ラムダ計算、その他の万能機械、停止性問題、型推論を解説

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Programming language Ruby

- Object oriented programming language Ruby
- Ruby is widely used in world-wide.
  - Web application development, such as Twitter (early days), github, and so on.
- Performance of Ruby interpreter is a matter.

One of performance bottleneck
Ruby's GC

- Conservative mark and sweep GC (from 1993)
- Issues:
  1. Low throughput
  2. Long pause time

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Traditional solution: well-known GC algorithms

- Generational GC (GenGC) to improve throughput by separating heaps per generations.
- Incremental GC (IncGC) to reduce pause time by doing GC steps incremental
- They needs “Write Barriers” (WB) to work correctly

Challenge

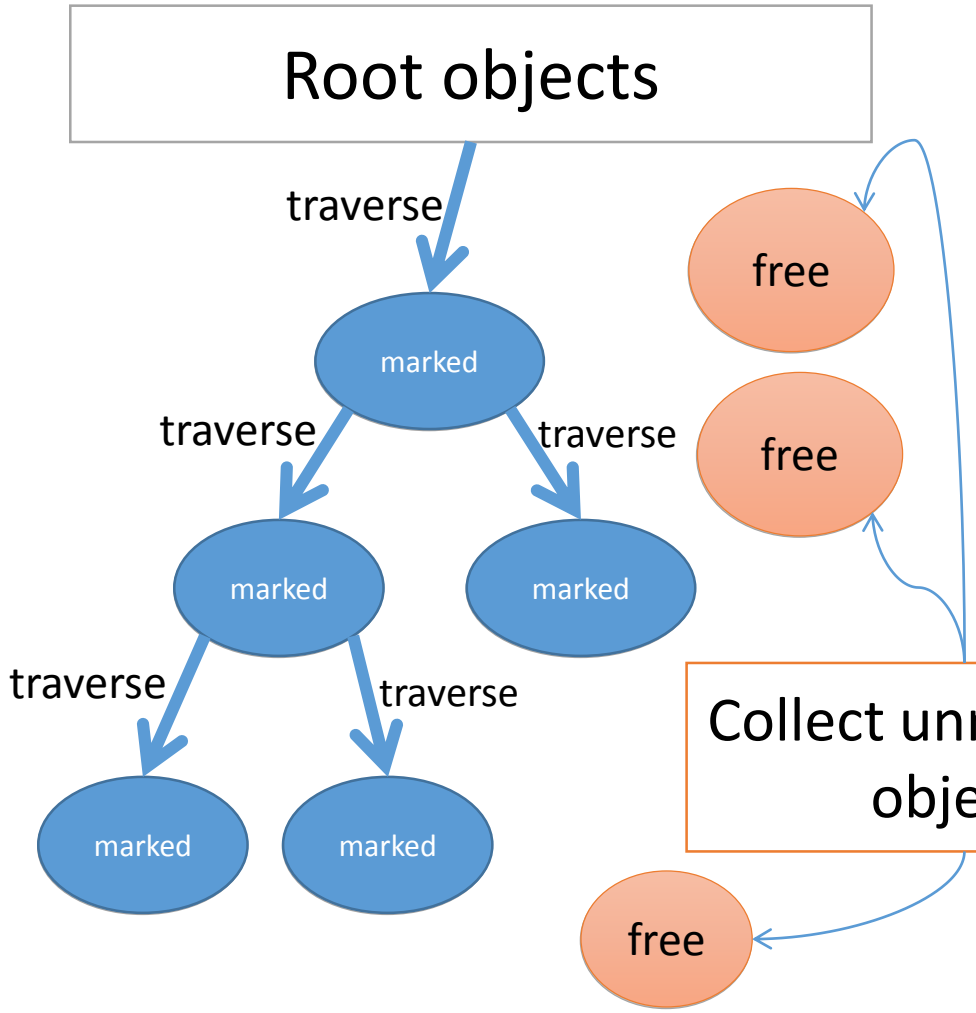
- Inserting perfect WBs is very difficult
  - Unfortunately, Ruby interpreter does not support WBs
  - High implementation cost for perfect WBs
  - API change becomes compatibility issue for existing extension libraries
- ***Allowing GenGC and IncGC with "Incomplete" WB insertions***
  - ***→ RGenGC: Restricted Generational GC algorithm***
  - ***→ RincGC: Restricted Incremental GC algorithm***

RGenGC: Restricted Generational GC algorithms

RGenGC algorithm is implemented at Ruby 2.1

which is already shipped.

Simple Mark & Sweep

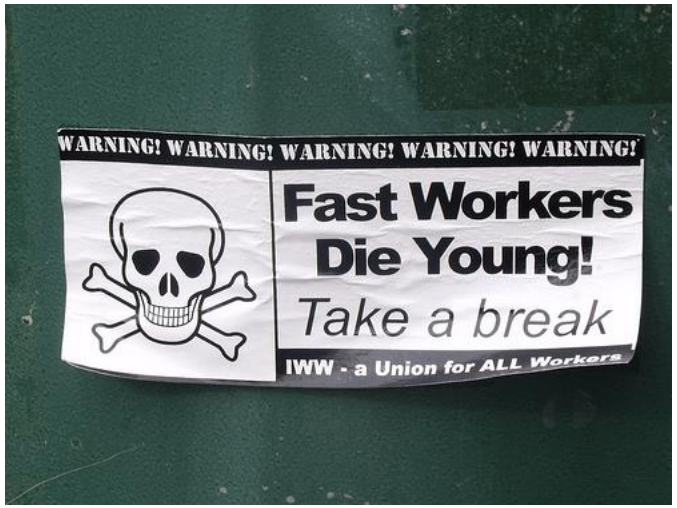


1. Mark reachable objects from root objects
2. Sweep ***unmarked*** objects (collection and de-allocation)

Generational GC (GenGC)

- Weak generational hypothesis:

“Most objects die young”



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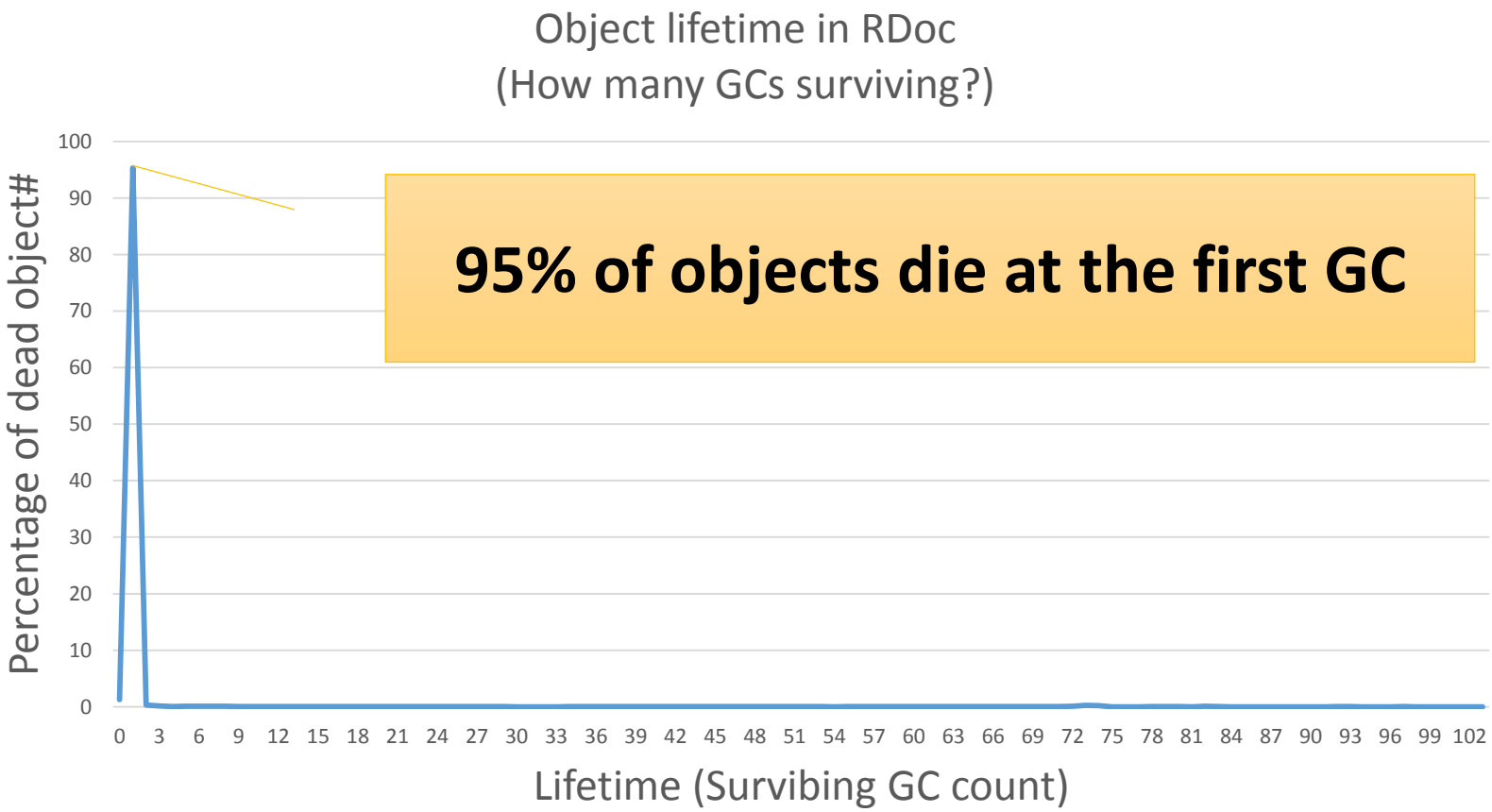
→ Concentrate reclamation effort only on the young objects

Generational hypothesis



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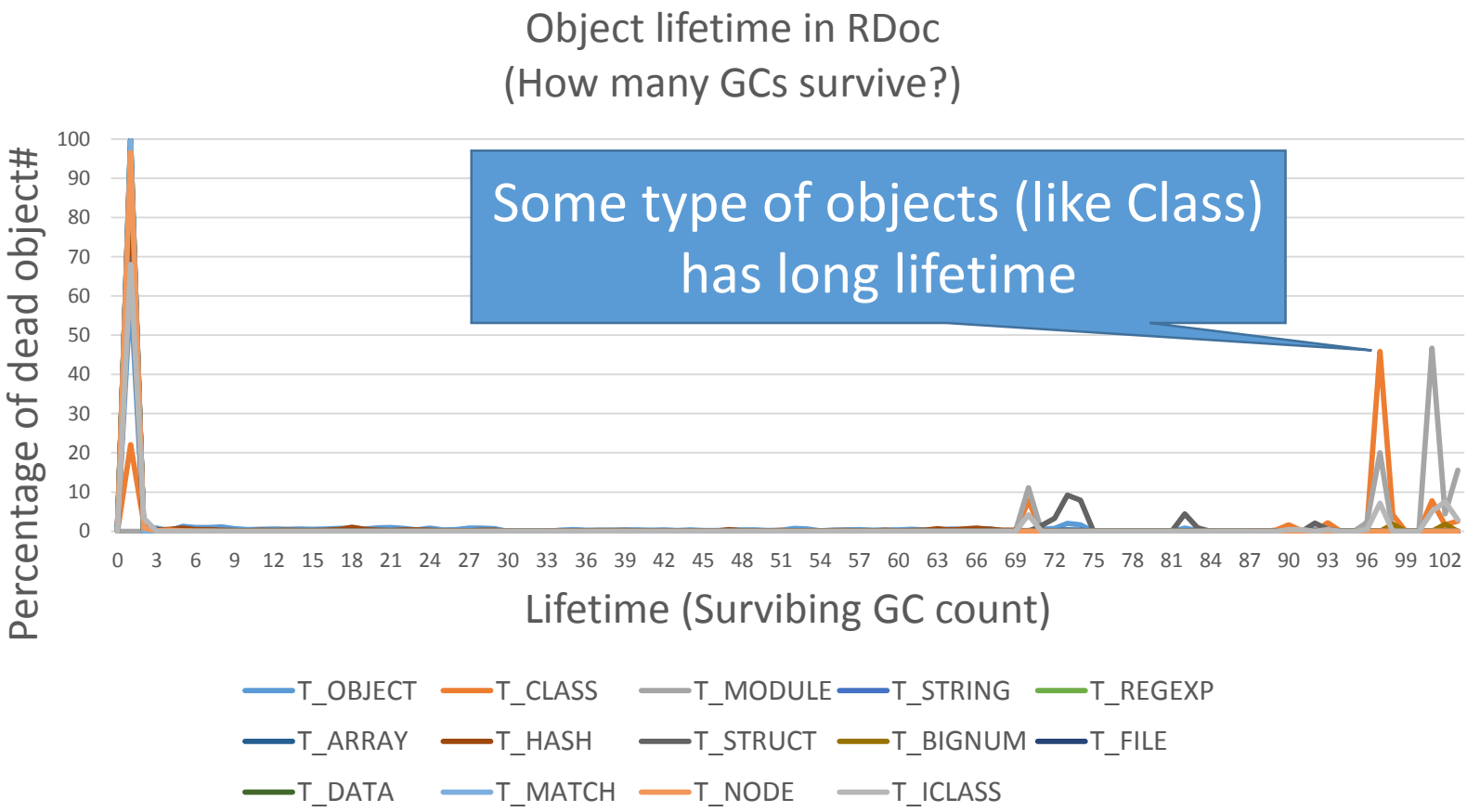
Generational hypothesis



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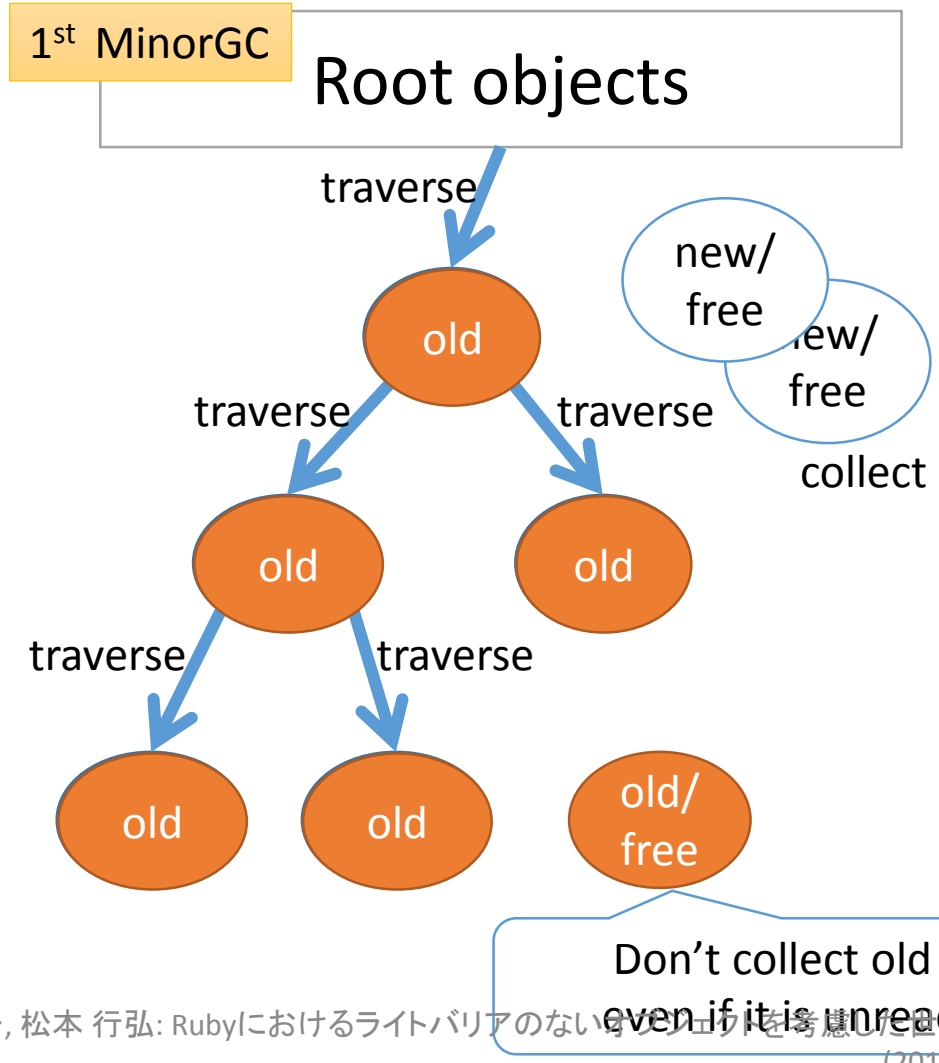
Generational GC (GenGC)

- Separate young generations and old generations
  - Create objects as youngest generation
  - Promote to old generations after surviving GCs
- Usually, GC on young space (minor GC)
- GC on both spaces if no memory (major/full GC)
- We can choose different GC algorithms on Minor GC and Major GC
  - In this presentation, we choose M&S for both GCs (because we choose M&S)

[Minor M&S GC]



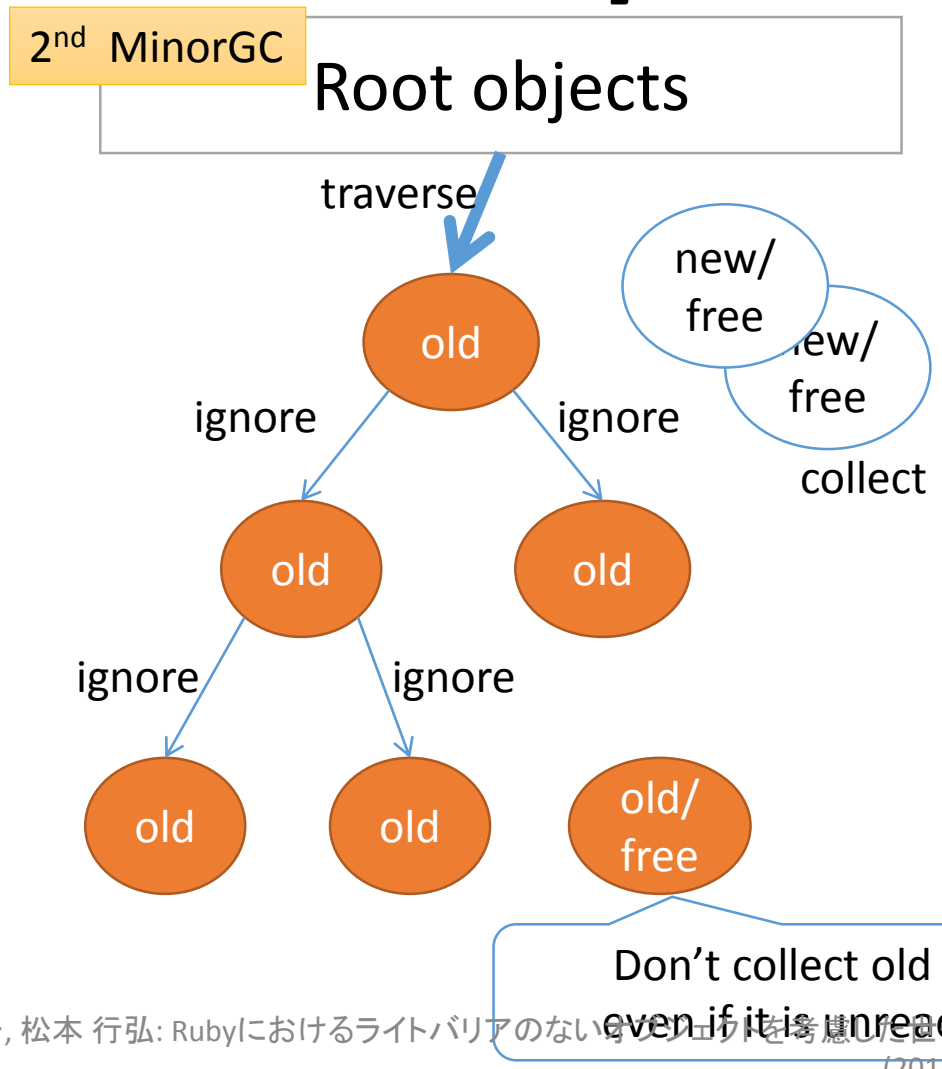
- Mark reachable objects from root objects.
  - Mark and **promote to old generation**
  - Stop traversing after old objects

→ Reduce mark overhead

- Sweep not (marked or old) objects

- Can't collect Some unreachable objects

RGenGC: Background: GenGC [Minor M&S GC]



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  - Mark and **promote to old generation**
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- Sweep not (marked or old) objects

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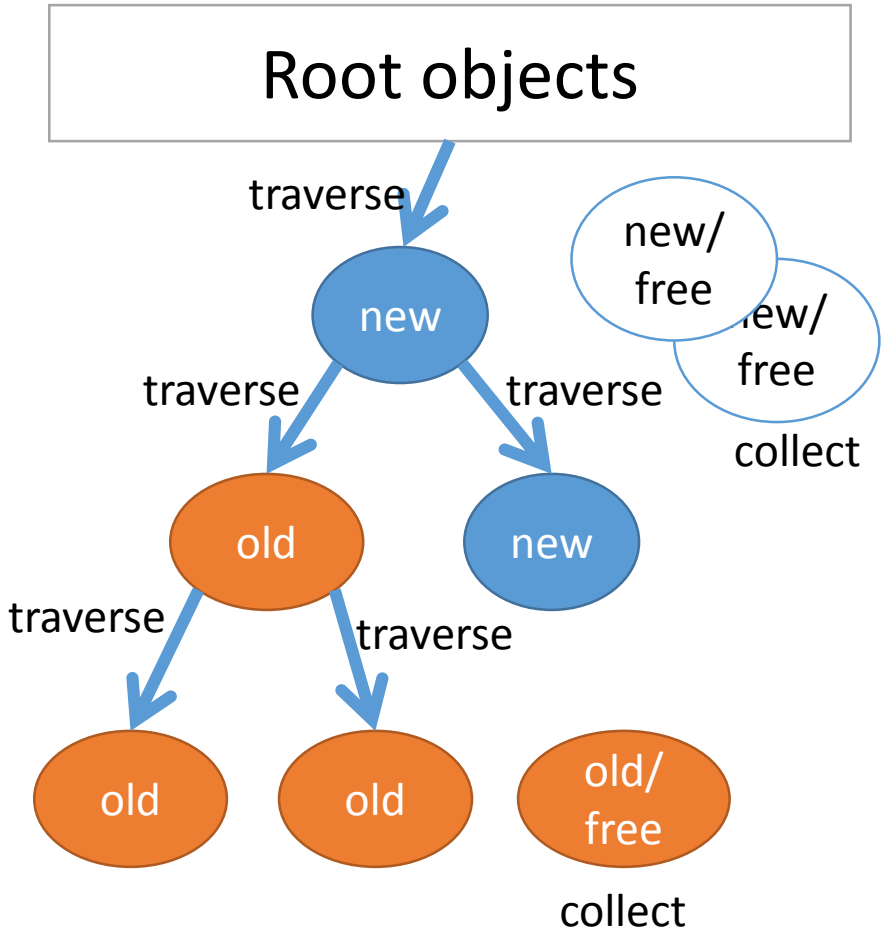
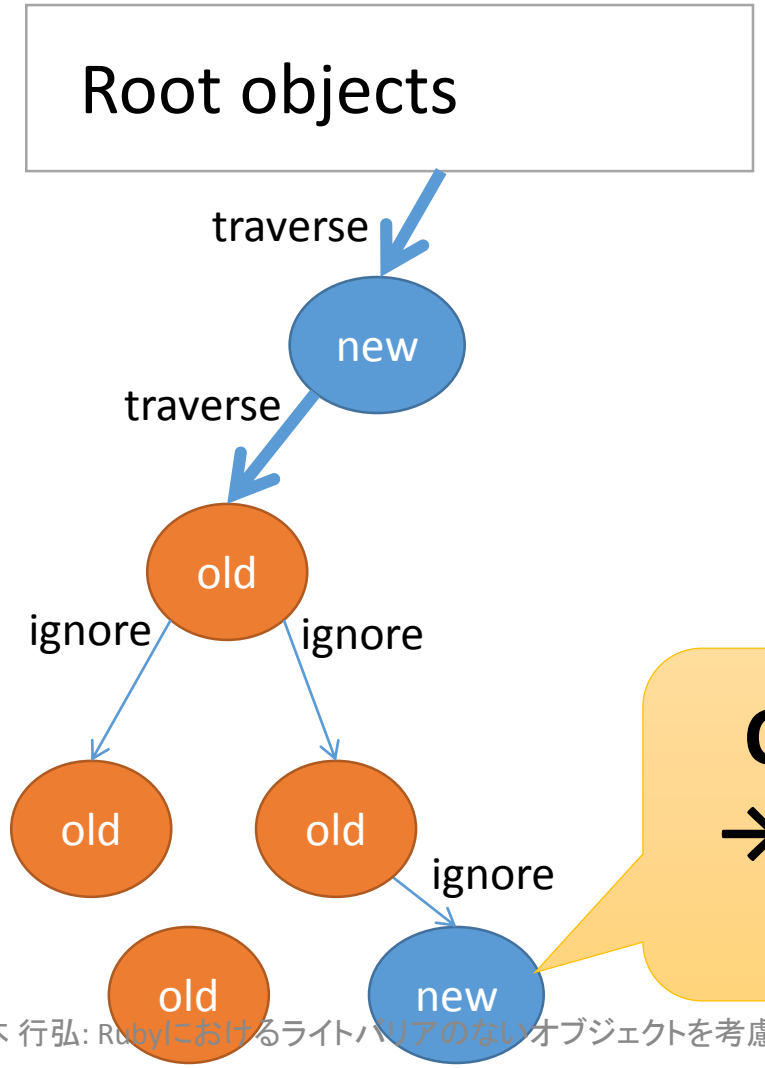
RGenGC: Background: GenGC [Major M&S GC]



- Normal M&S
- Mark reachable objects from root objects
  - Mark and **promote to old gen**
- Sweep unmarked objects

- *Sweep all unreachable (unused) objects*

RGenGC: Background: GenGC Problem: mark miss



- Old objects refer young objects

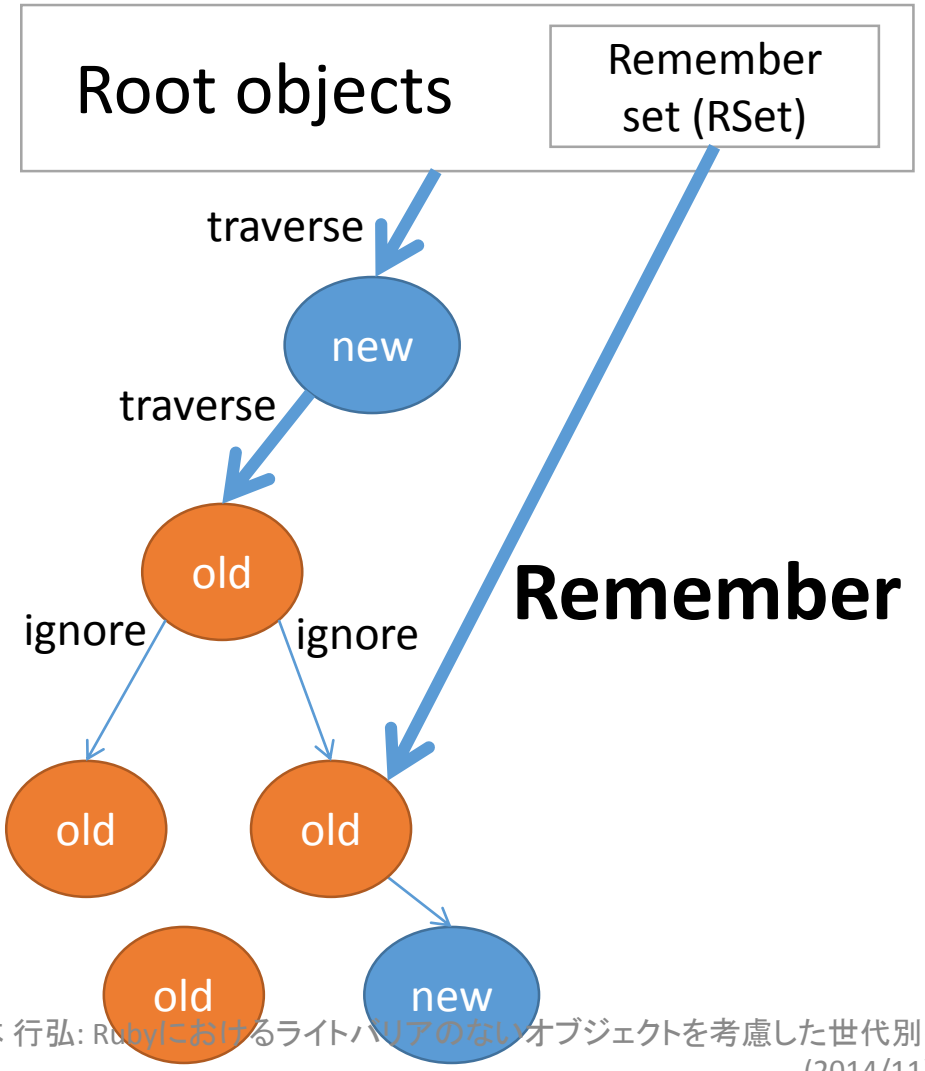
→ Ignore traversal of old object

→ Minor GC causes marking leak!!

- Because minor GC ignores referenced objects by old objects

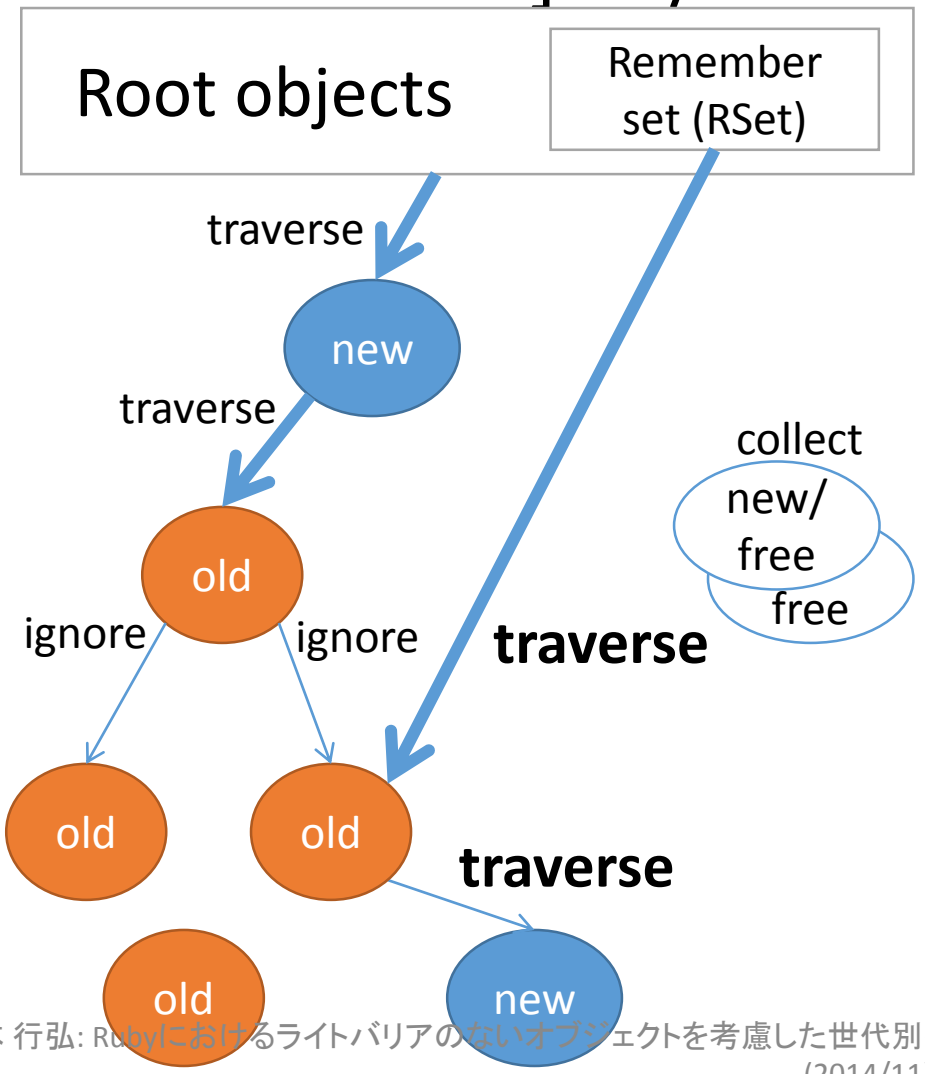
Can't mark new object!
→ Sweeping living object!
(Critical BUG)

RGenGC: Background: GenGC Introduce Remember set (Rset)



1. **Detect** creation of an [old->new] type reference
2. Add an [old object] into **Remember set (RSet)** if an old object refer new objects

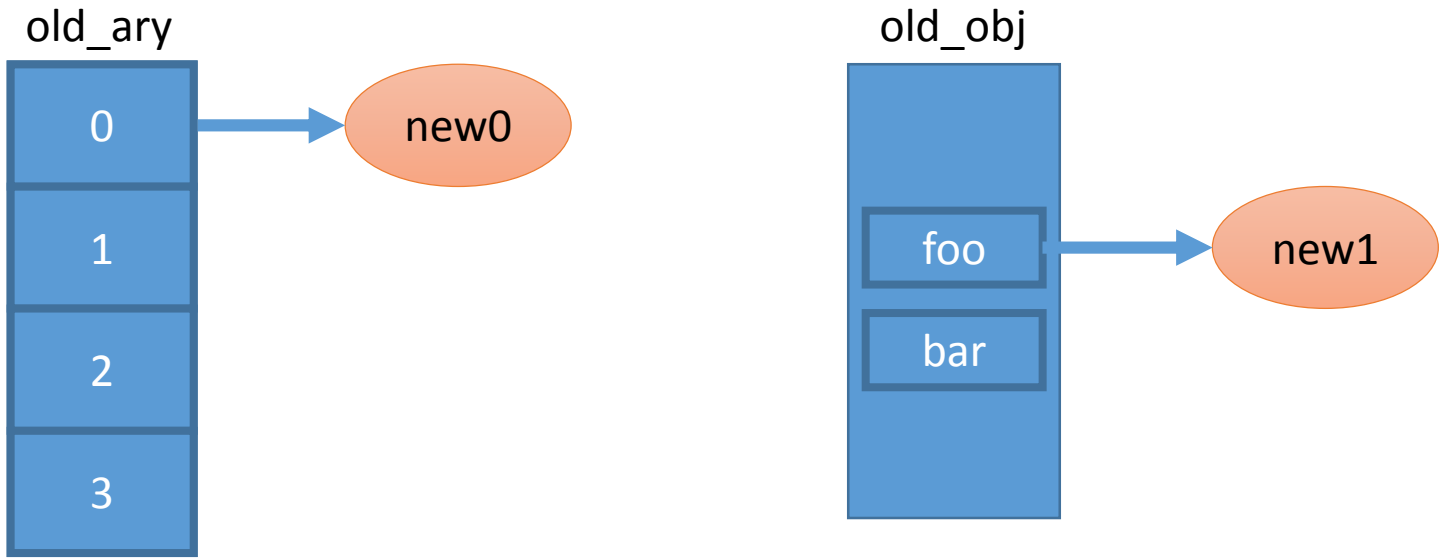
RGenGC: Background: GenGC [Minor M&S GC] w/ RSet



1. Mark reachable objects from root objects
   - **Remembered objects are also root objects**
2. Sweep not (marked or old) objects

Write barriers in Ruby

- Write barrier (WB) example in Ruby world
  - (Ruby) old_ary[0] = new0 # [old_ary → new0]
  - (Ruby) old_obj.foo = new1 # [old_obj → new1]



Difficulty of inserting write barriers

- To introduce generational garbage collector, WBs are necessary to detect [old→new] type reference
- “Write-barrier miss” causes terrible failure
  1. WB miss
  2. Remember-set registration miss
  3. (minor GC) marking-miss
  4. **Collect live object → Terrible GC BUG!!**

Problem: Inserting WBs into C-extensions (C-exts)

- All of C-extensions need perfect Write-barriers
  - C-exts manipulate objects with Ruby's C API
  - C-level WBs are needed
- Problem: How to insert WBs into C-exts?
  - There are many WB required programs in C-exts
    - Example (C): RARRAY_PTR(old0)[0] = new1
    - Ruby C-API doesn't require WB before
  - CRuby interpreter itself also uses C-APIs
- How to deal with?
  - We can rewrite all of source code of CRuby interpreter to add WB, **with huge debugging effort!!**
  - We can't rewrite all of C-exts which are written by 3rd party

Problem: Inserting WBs into C-extensions (C-exts)

Two options

		Performance	Compatibility
1	Give up GenGC	Poor	Good (No problem)
2	GenGC with re-writing all of C exts	Good	Most of C-exts doesn't work

Ruby 2.0 and earlier
conservative choice

Trade-off of Speed and Compatibility

Invent 3rd option

		Performance	Compatibility
1	Give up GenGC	Poor	Good (No problem)
2	GenGC with re-writing all of C codes	Good	Most of C-exts doesn't work
3	Use new RGenGC	Good	Most of C-exts works!!

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RGenGC:
Key idea

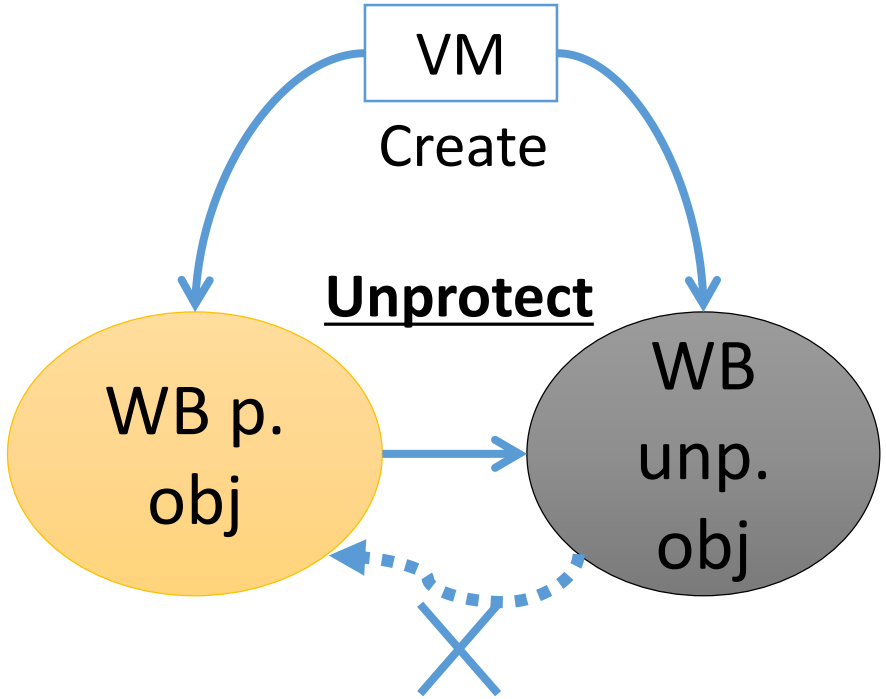
- Introduce **WB unprotected objects**

RGenGC:
Key idea

- Separate objects into two types
  - WB protected objects
  - WB unprotected objects
- We are not sure that a WB unprotected objects point to new objects or not
- Decide this type at creation time
  - A class care about WB → WB protected object
  - A class don’t care about WB → WB unprotected object

RGenGC:
Key idea

- Normal objects can be changed to WB unprotected objects
  - “WB unprotect operation”
  - C-exts which don’t care about WB, objects will be WB unprotected objects
  - Example
    - ptr = RARRAY_PTR(ary)
    - In this case, we can’t insert WB for ptr operation, so VM shade “ary”

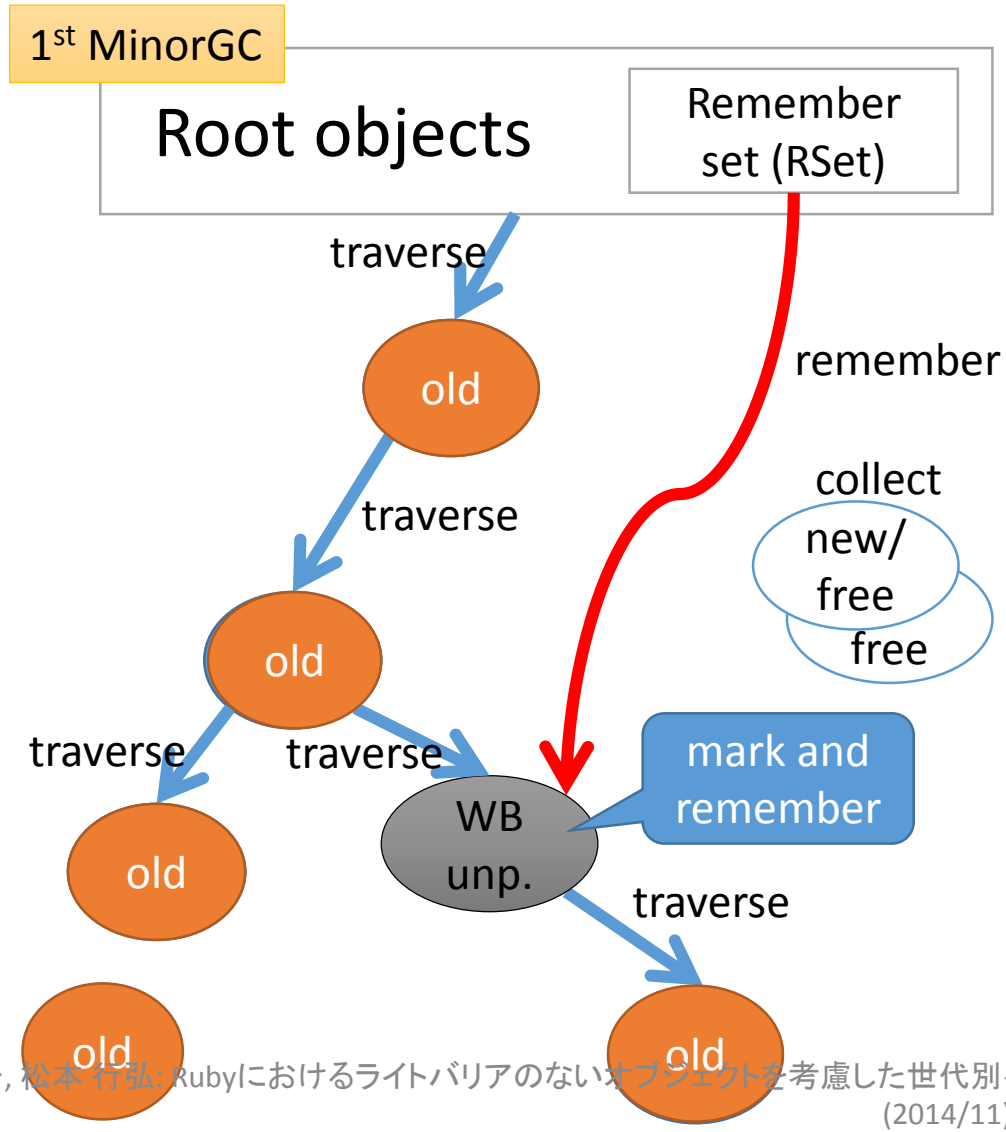


Now, WB unprotected object **can’t** change into WB p. object

RGenGC
Rule

- Treat “WB unprotected objects” correctly
  - At Marking
  1. Don’t promote WB unprotected objects to old objects
  2. Remember WB unprotected objects pointed from old objects
  - At WB unprotect operation for old WB protected objects
  1. Demote objects
  2. Remember this unprotected objects

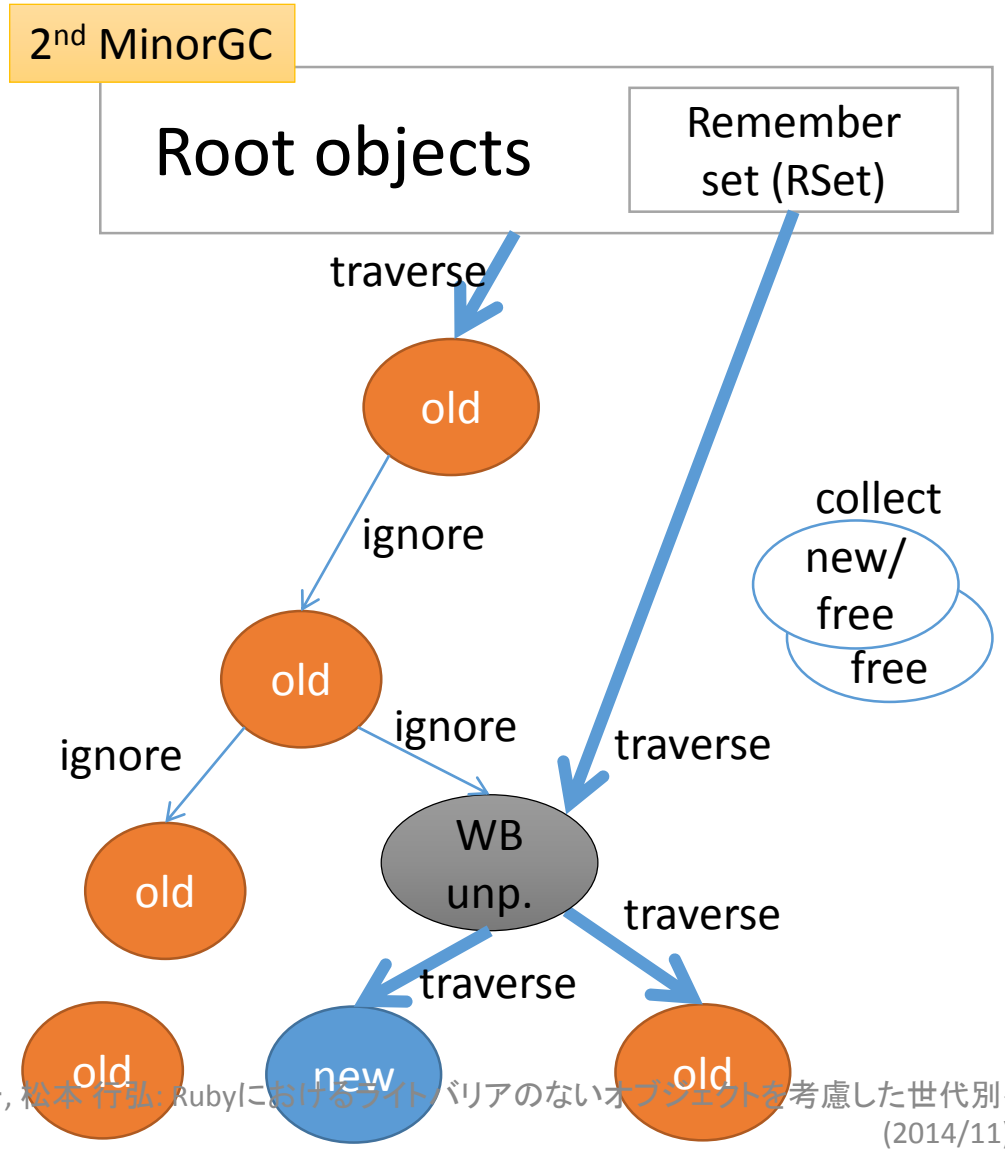
RGenGC [Minor M&S GC w/WB unp. objects]



- Mark reachable objects from root objects
  - Mark WB unprotected objects, and ***don't promote*** them to old gen objects
  - If WB unprotected objects **pointed from old objects**, then **remember this WB unprotected objects** by RSet.

    → Mark WB unprotected objects every minor GC!!

RGenGC [Minor M&S GC w/WB unp. objects]



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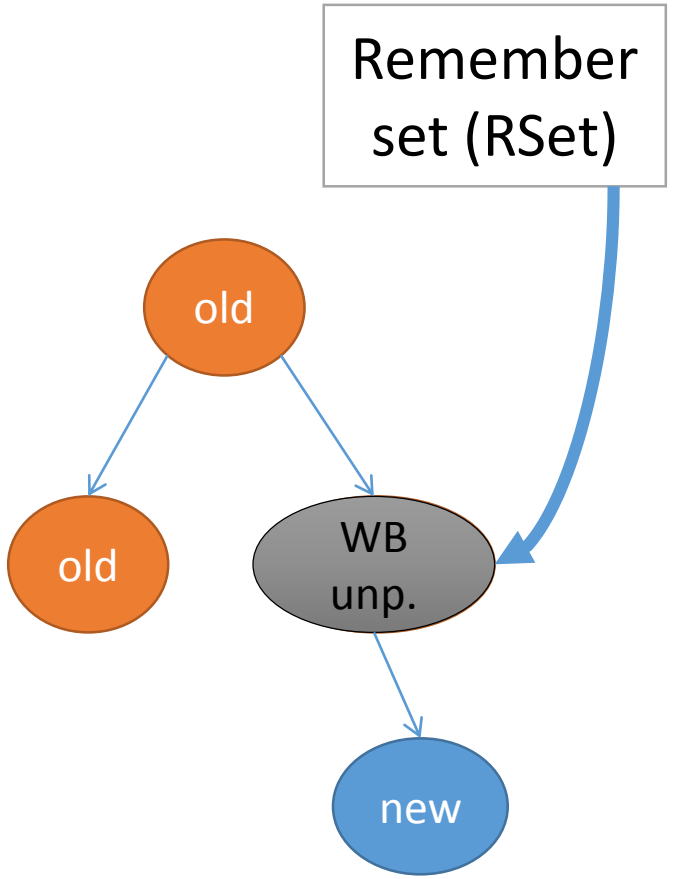
RGenGC [Unprotect operation]



- Anytime Object can give up to keep write barriers

  → [Unprotect operation]

- Change old WB protected objects to WB unprotected objects
  - Example: RARRAY_PTR(ary)

  (1) Demote object (old → new)

  (2) Register it to Remember Set

RGenGC
Discussion: Pros. and Cons.

- Pros.
  - Allow WB unprotected objects
    - **100% compatible** w/ existing extensions which don't care about WB
    - A part of CRuby interpreter which doesn't care about WB
  - **Inserting WBs step by step, and increase performance gradually**
    - We don't need to insert all WBs into interpreter core at a time
    - We can concentrate into popular (effective) classes/methods.
    - We can ignore minor classes/methods.
  - Simple algorithm, easy to develop

RGenGC
Discussion: Pros. and Cons.

- Cons.
  - Increasing “unused, but not collected objects until full/major GC
    - Remembered normal objects (caused by traditional GenGC algorithm)
    - Remembered WB unprotected objects (caused by RGenGC algorithm)
  - WB insertion bugs (GC development issue)
    - WB protected objects need correct/perfect WBs. However, inserting correct/perfect WBs is difficult.
    - This issue is out of scope

Issue of RGenGC: Long pause time

- Good: RGenGC achieves ***high throughput***
- Good: Minor GC stops only ***short pause time***
- Bad: Major GC still stops ***long pause time***

→ ***Introducing Incremental GC for major GC***

	Generational GC	Incremental GC	Gen+Inc GC
Throughput	High	Low (a bit slow)	High
Pause time	Long	Short	Small

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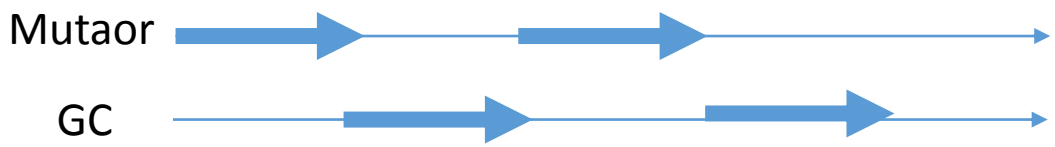
RincGC: Restricted Incremental GC algorithms

RincGC algorithm is begin implemented for Ruby 2.2.

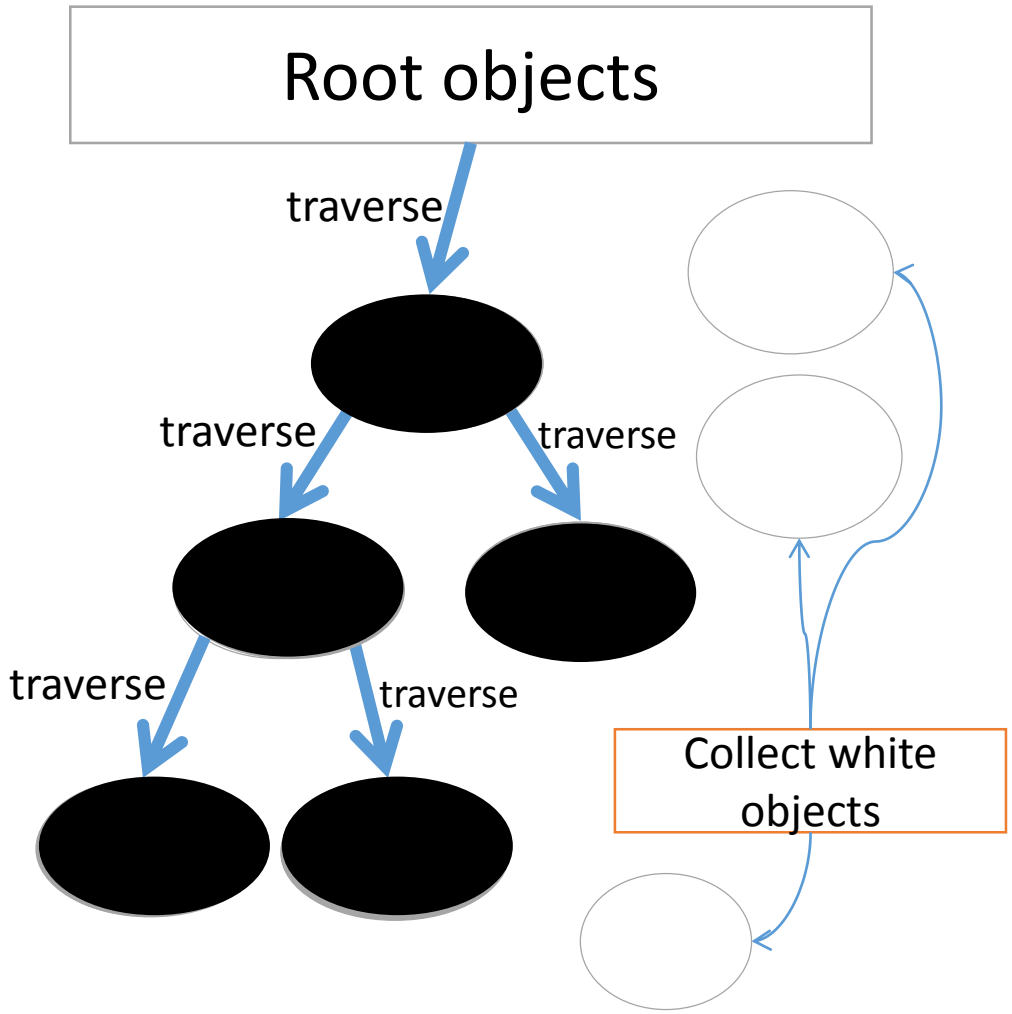
Incremental GC

- GC steps incrementally
  - Interleaving with mutators and GC process.



- Using 3 colors
  - White objects is not traversed objects
  - Grey objects can point white objects
  - Black objects only point grey or black objects

Incremental GC



1. Color all objects “white”
2. Grey root objects
3. Choose a grey object and grey reachable white objects, and black the chosen object
4. Finish marking when no grey objects
5. Sweep white objects as ***unmarked*** objects

Do step 3 incrementally

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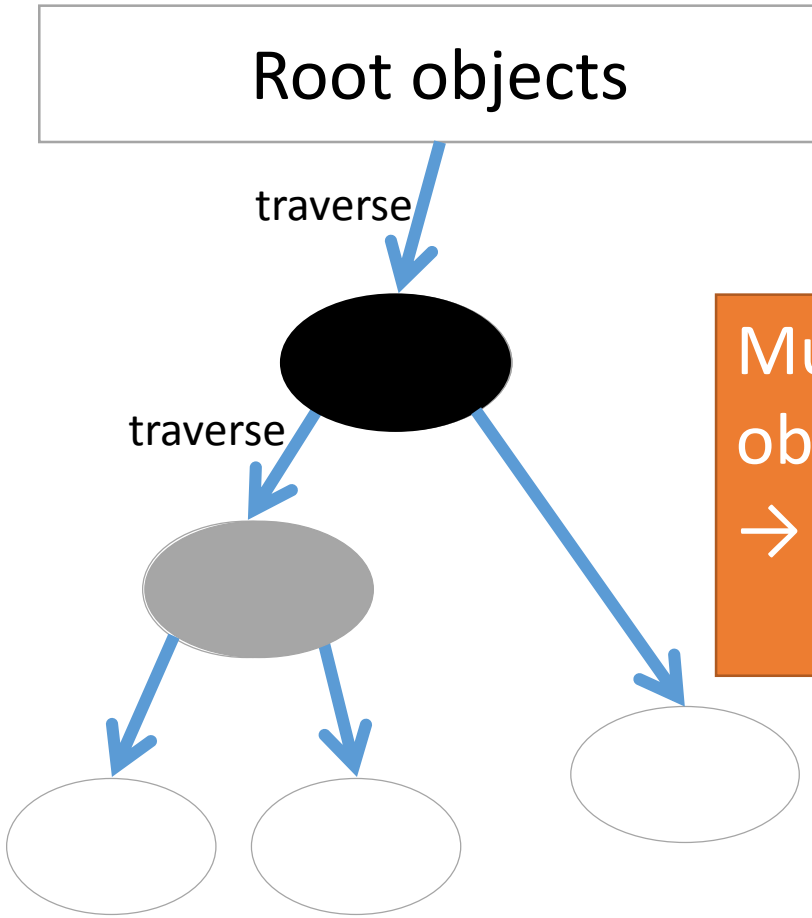
Incremental GC requires WBs



Mutator can add reference from a Black object to a white object!!
→ Mark miss!
No more traversal from black objects

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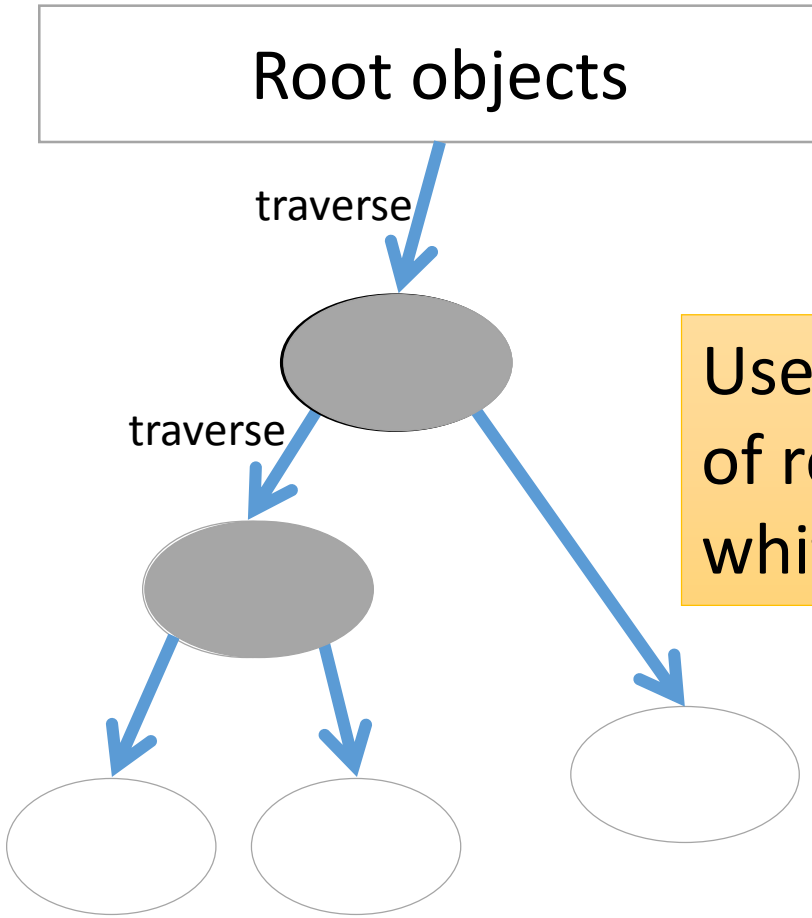
Incremental GC requires WBs

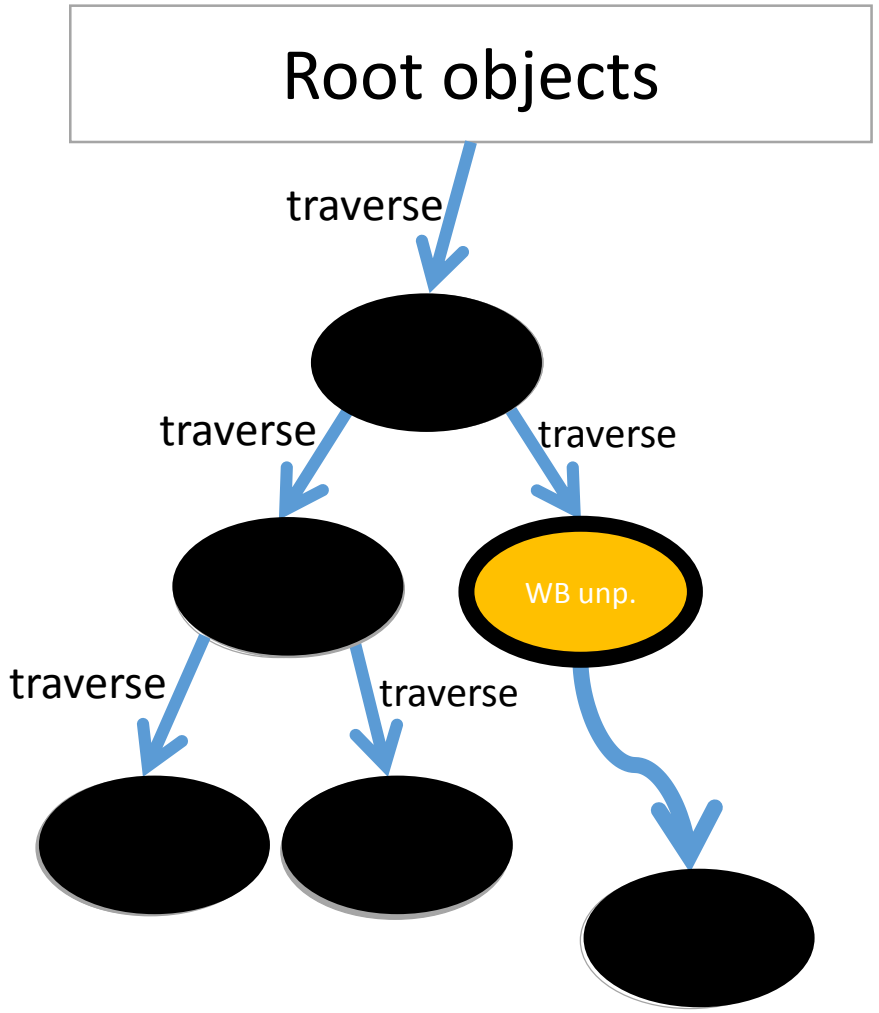


Use write barrier to detect an addition of references from black objects to white objects, and grey black objects

RincGC: Restricted Incremental GC using WB-unprotected objects

- Use WB unprotected objects like RGenGC
- Introducing a new rule: “Scan all black WB unprotected objects at the end of incremental GC at once”
  - WB unprotected objects can point white objects, so black such white objects without interleaving any mutators

RincGC



1. Color all objects “white”
2. Grey root objects
3. Choose a grey object and grey reachable white objects, and black the chosen object
4. Finish marking when no grey objects
5. **<u>Scan all black WB unprotected objects at once</u>**
6. Sweep white objects as *unmarked* objects

RincGC: Discussion

- Long pause time
  - This technique can introduce long pause time, relative to the number of WB unprotected objects at last. This is why this algorithm is named “Restricted”
  - Shorter pause time than “Minor GC” of RGenGC.

Implementation

Ruby's implementation
WB protected/unprotected

- Make popular class instances WB protected
  - String, Array, Hash, and so on
- Implement "unprotect operation" for Array and so on
- Remain WB unprotected objects
  - Difficult to insert WBs: a part of Module, Proc (local variables) and so on.
  - Minor features

Ruby's implementation
Data structure

- Introduce 2 bits age information to represent young and old objects
  - Age 0 to 2 is young object
  - Age 3 is old object
  - Surviving 1 GC increase one age
- Add 3 bits information for each objects (we already have mark bit)
  - WB unprotected bit
  - Long lived bit (old objects or remembered WB unprotected objects)
  - Remembered old object bit / Marking (Grey) bit
    - They can share 1 bit field because the former is used only at minor GC and the latter is used only at major GC (incremental GC)

Ruby's implementation
Bitmap technique

- Each bits are managed by bitmap technique
  - Easy to mange remember set
  - Fast traversing
  - Easy to get a set
    - Remember set: (Remembered old object bitmap) | (Long lived bitmap & WB unp. Bitmap)
    - Living unprotected objects: (mark bitmap & WB unprotected bitmap)

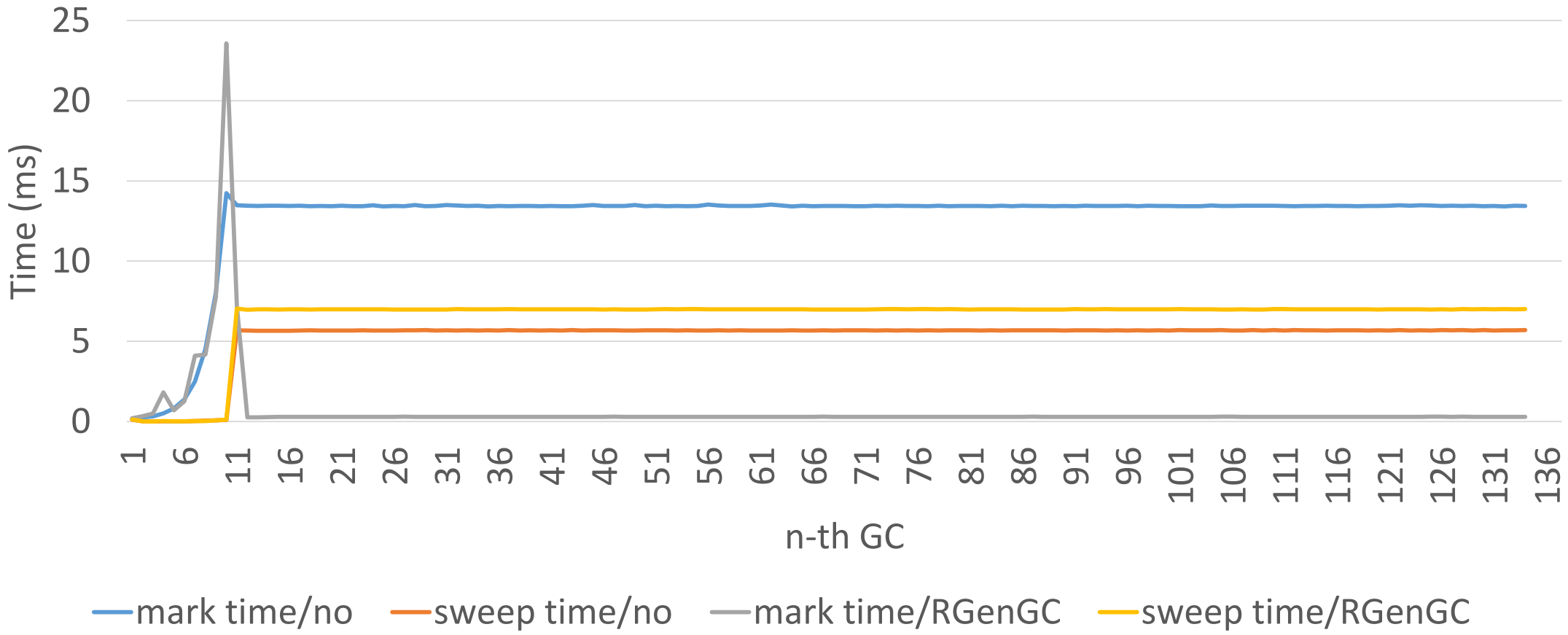
Evaluation

- RGenGC
  - Micro-benchmark
  - Application benchmark
- RincGC
  - Micro-benchmark
  - Application benchmark
- Environment
  - Intel(R) Core(TM) i7-4930K CPU @ 3.40GHz (Thanks Prof. Sugaya, Shibaura-IT)
  - Ubuntu 14.04.1 LTS (GNU/Linux 3.13.0-37-generic x86_64)
  - ruby 2.2.0dev (2014-11-09 trunk 48334) [x86_64-linux]

RGenGC: Micro-benchmark

```
# Make 1M objects (long lived)
ary = (1..1_000_000).map{|e| Object.new}
# Make short-lived 100M objects
100_000_000.times{Object.new}
```

RGenGC: Micro-benchmark



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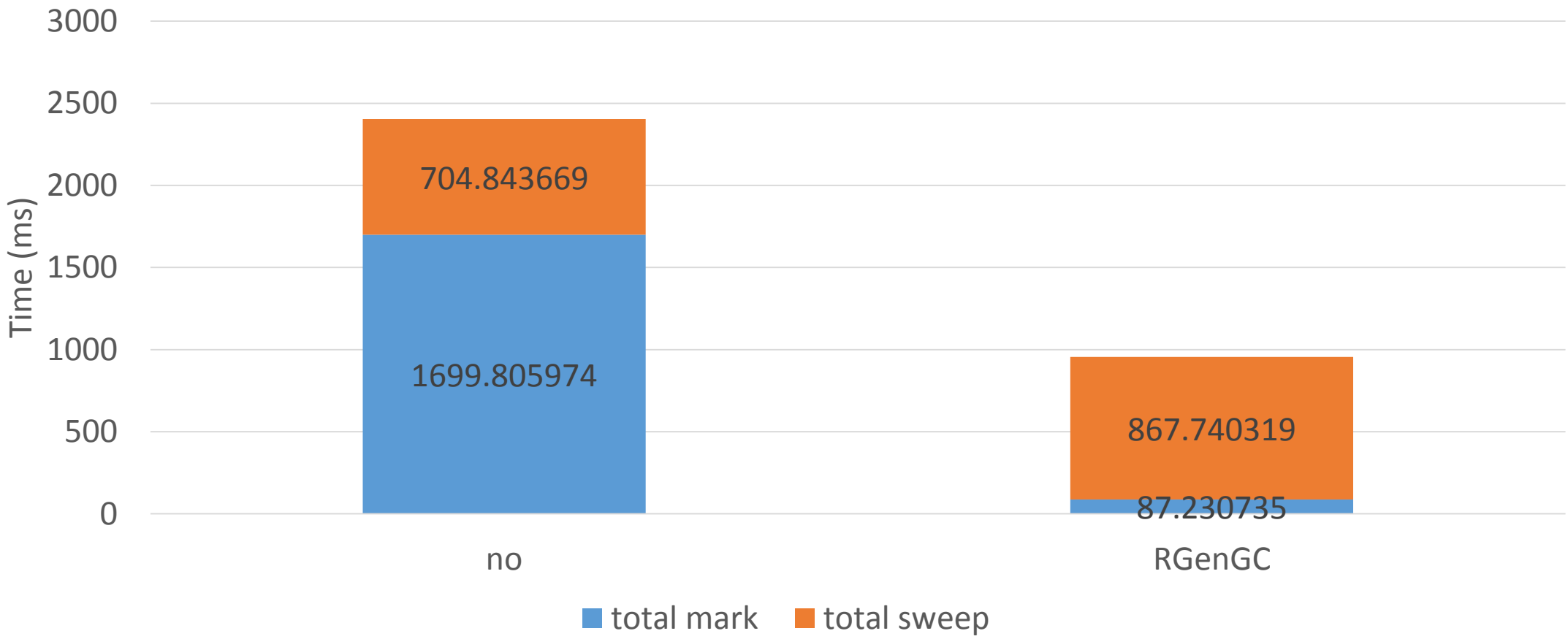
RGenGC: Micro-benchmark



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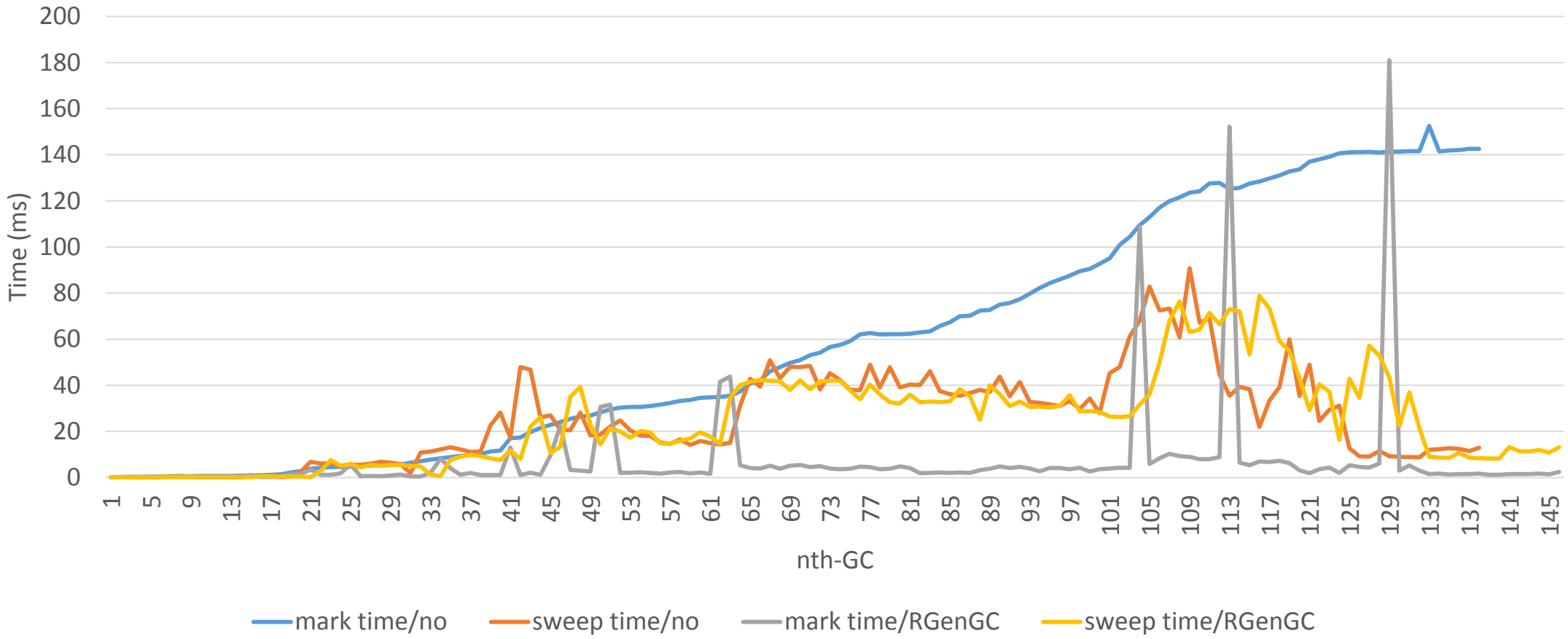
RGenGC: Rdoc application



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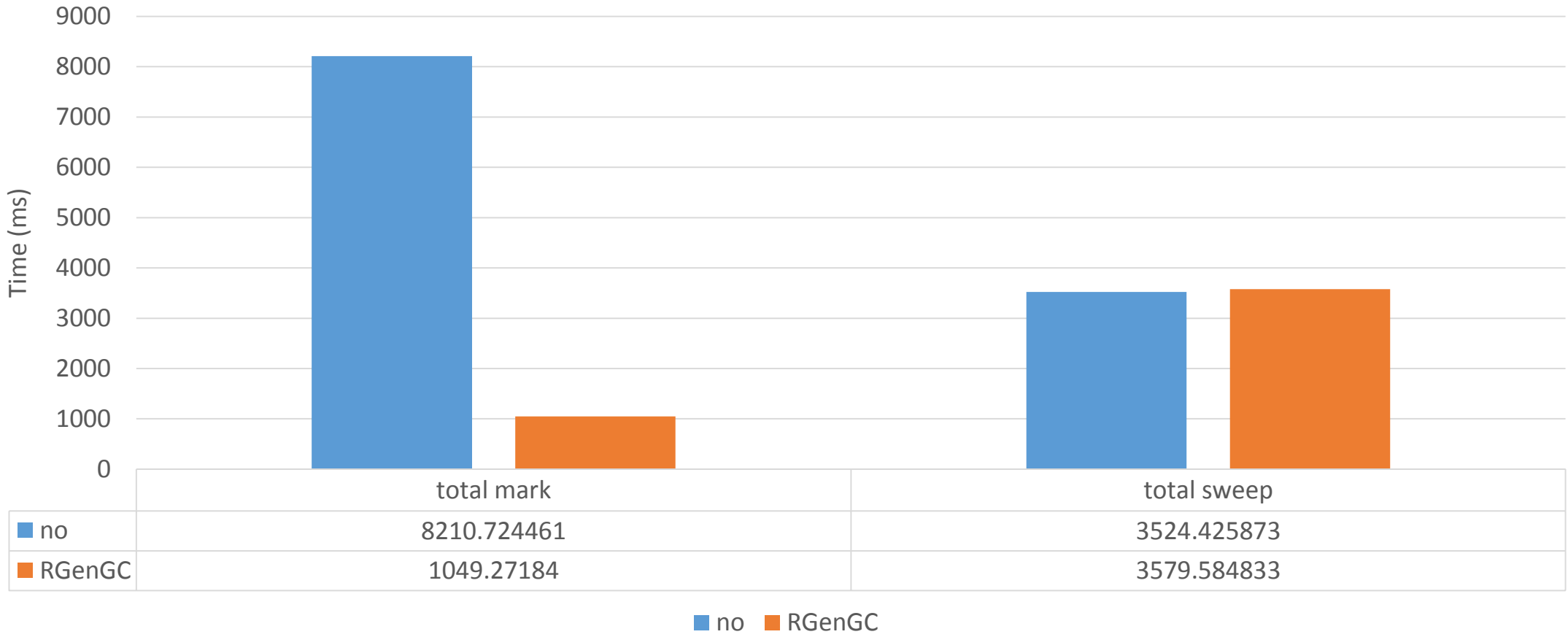
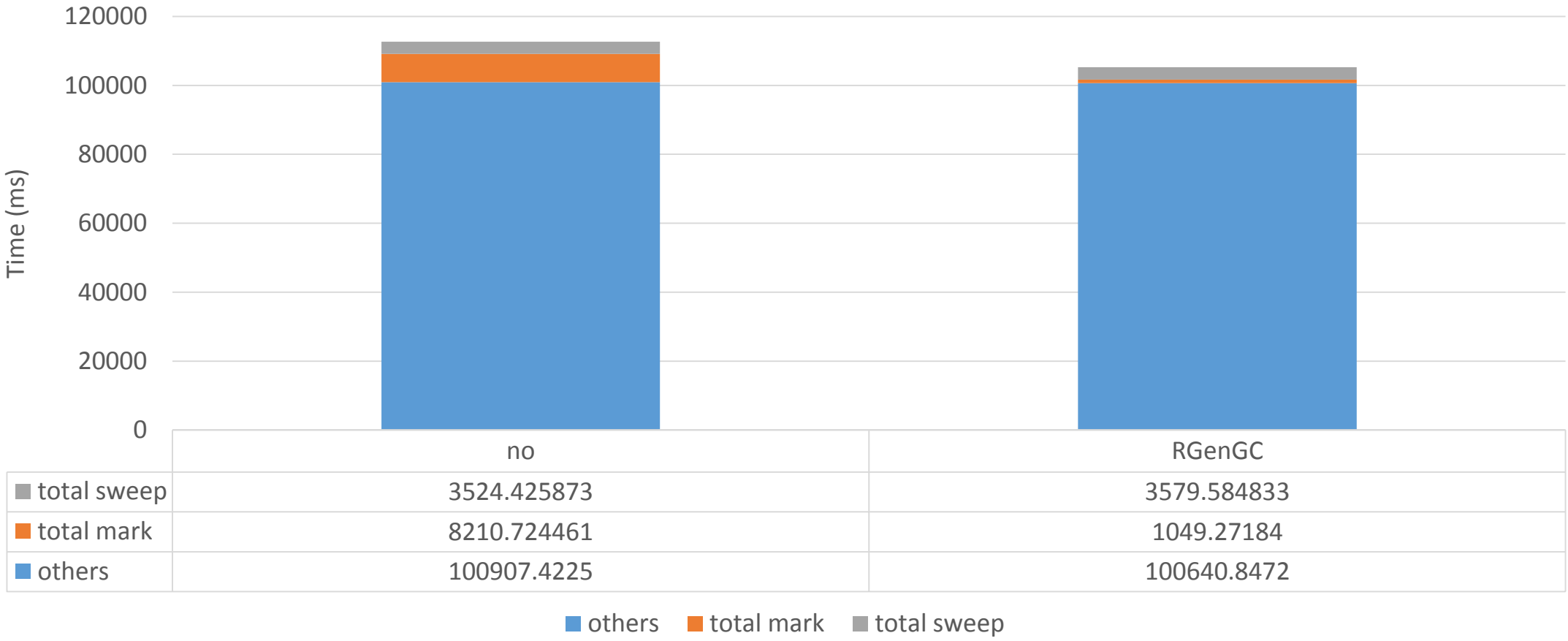
RGenGC: Rdoc application



	total mark	total sweep
no	8210.724461	3524.425873
RGenGC	1049.27184	3579.584833

笹田 耕一, 松本 行弘: Rubyにおけるライトバリアのないオブジェクトを考慮した世代別インクリメンタルGCの実装, 情報処理学会 第101回プログラミング研究発表会 (2014/11)

RGenGC: Rdoc application



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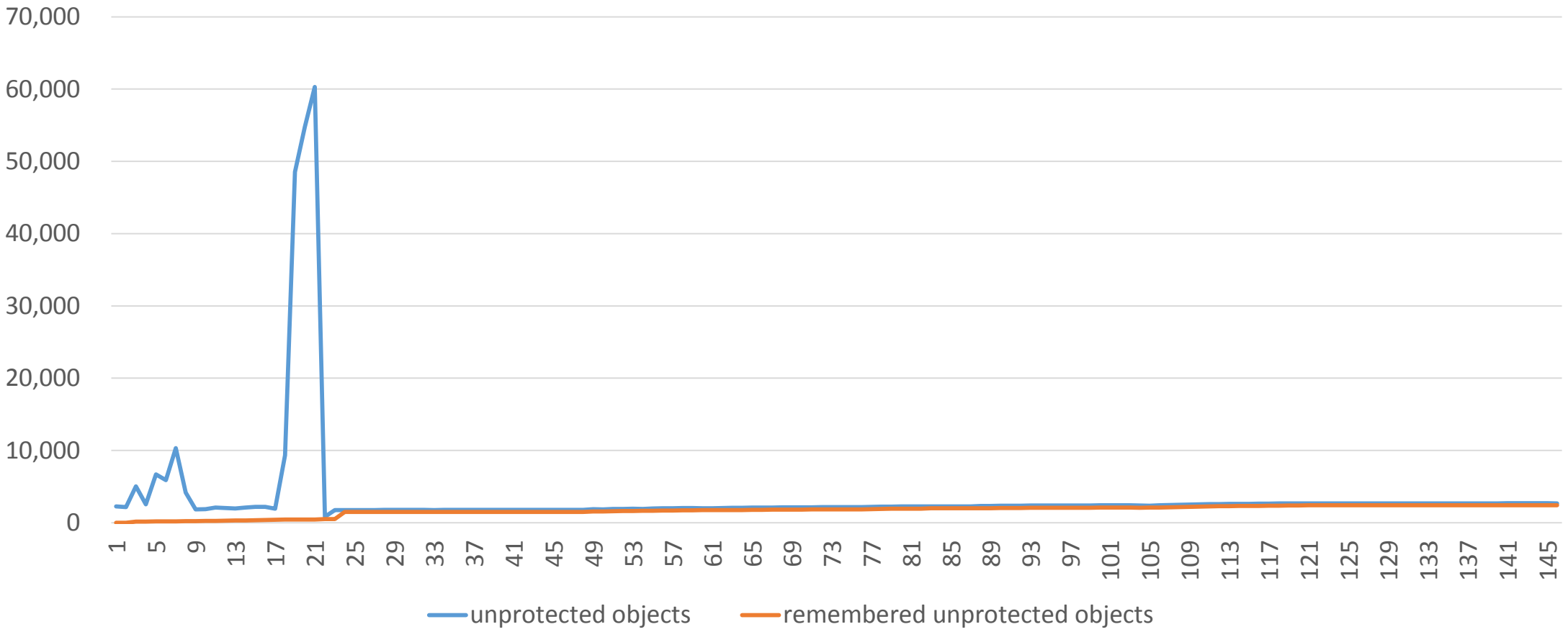

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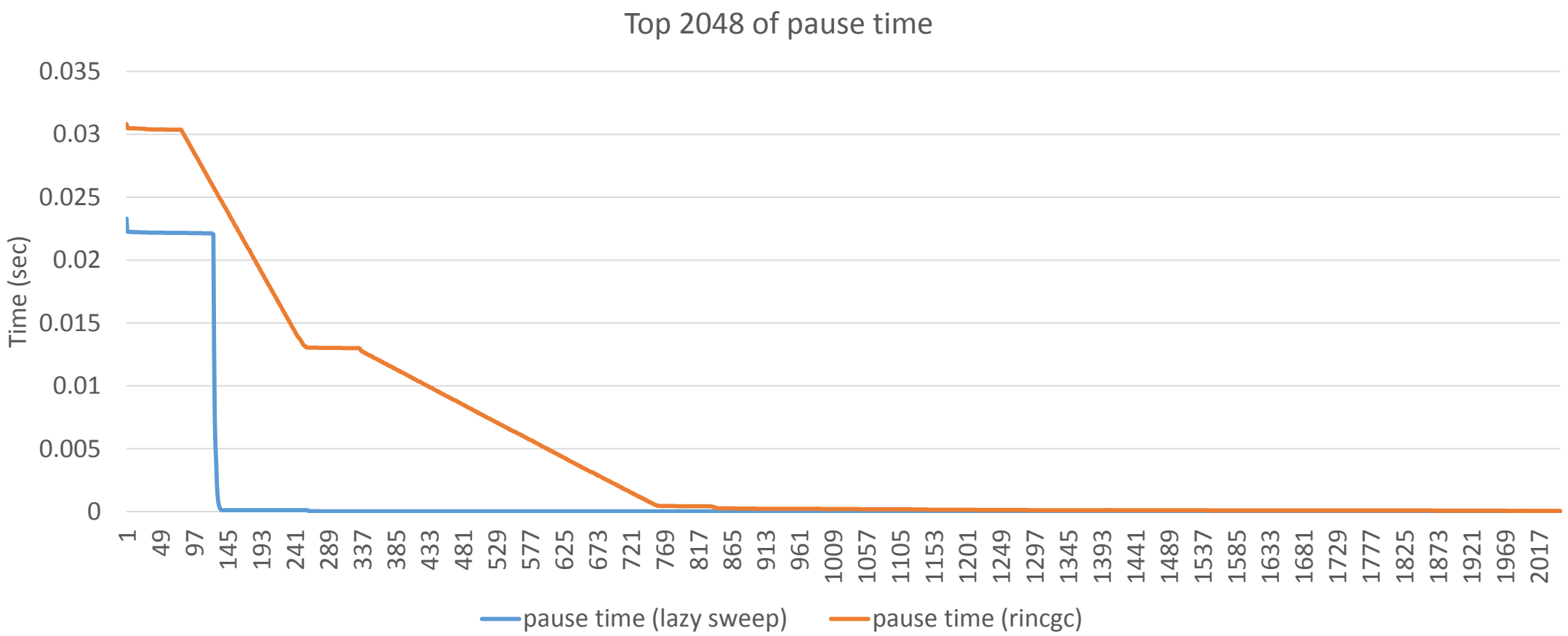
RincGC: Micro-benchmark



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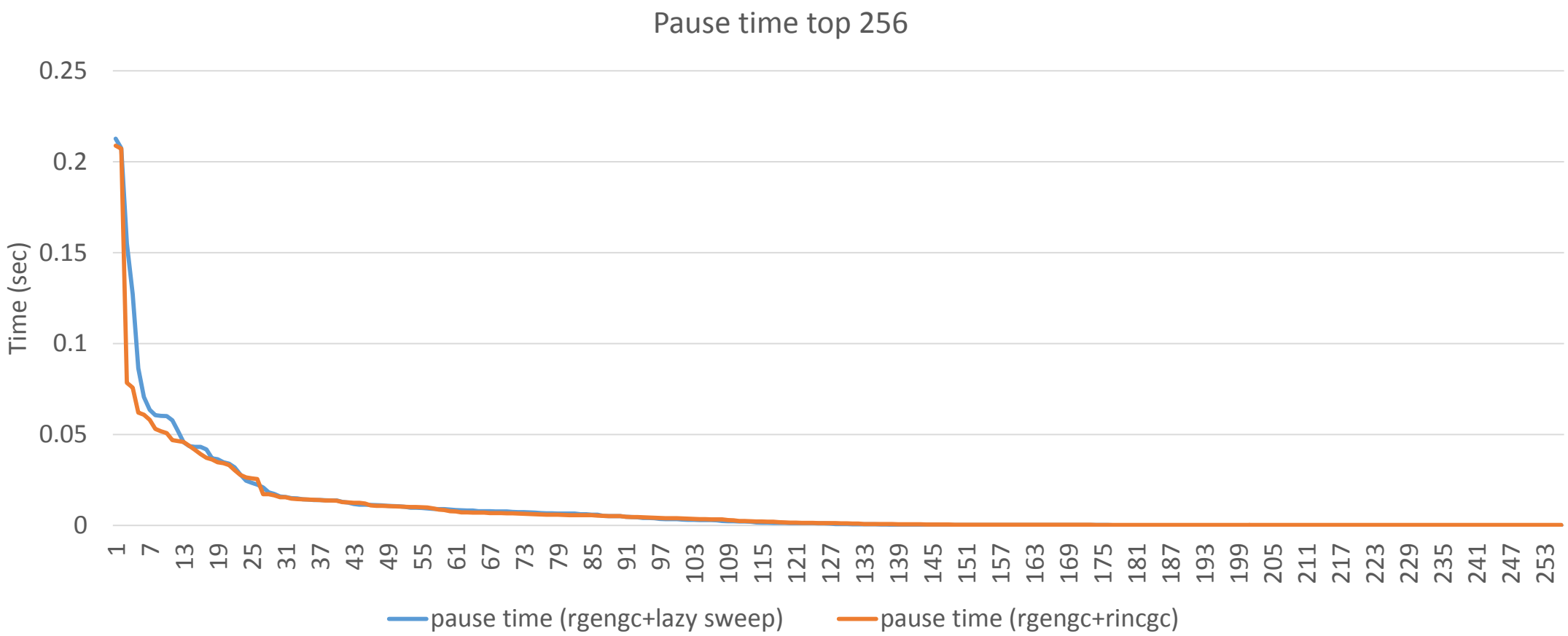
RincGC: Rdoc application



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Related work

- Unexpectedly, only a few work. Maybe most of interpreters are initially developed using write barriers.
- Memory protection is widely used for card marking instead of fine-grain write barriers.
- Hanai, et.al. proposed auto WB insertion technique by analyzing interpreter source code.
- Aikawa, et.al. proposed WB location detection using memory protection technique.

Future work

- Improve performance of sweep-phase
- Tuning RincGC to reduce pause time

Summary

- 背景
  - Ruby処理系にはライトバリア（WB）が入っていないし、実装大変
  - 世代別GC、インクリメンタルGCはWBが無いと実装できない
- 本研究の貢献
  - 完璧にWBが入って無くても出来るアルゴリズムを考えました
- 実世界への貢献
  - この世代別GCが入ったRuby 2.1は2013年12月にリリース済み
  - このインクリメンタルGCを追加したRuby 2.2を2014年12月にリリース予定