Concurrent, Parallel Garbage Collection in Linear Time

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- Two main categories:
    - *Tracing Garbage Collection*
    - *Reference Counting*

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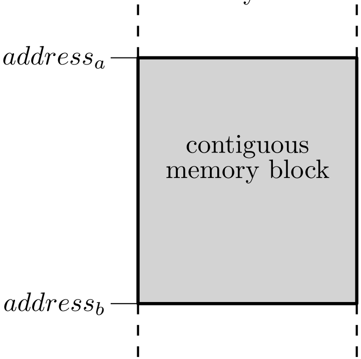
Memory Model



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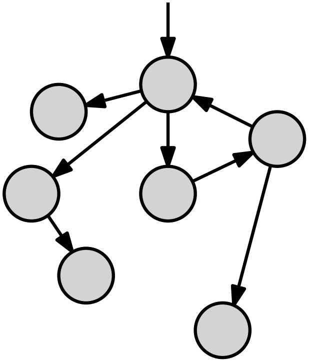

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Cons

- Consumes computing resources.
- Unpredictable.

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Basics

- Every object stores a count of references to itself
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- strong and weak references
- correct cycle detection
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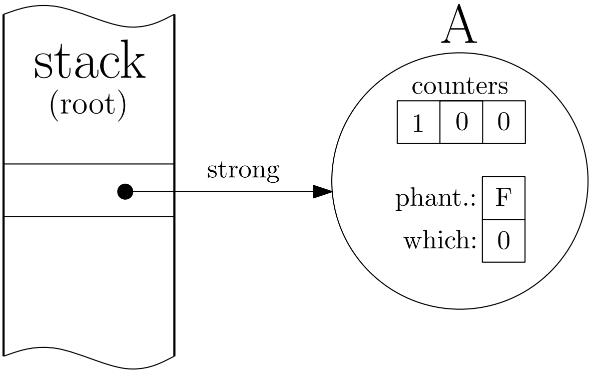

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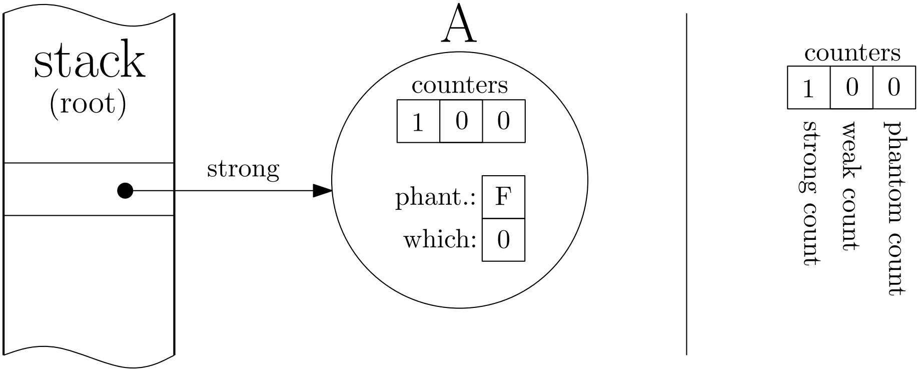

stack

(root)

strong

A

counters

1	0	0

phant.: F

which: 0

counters

1	0	0
strong count	weak count	phantom count

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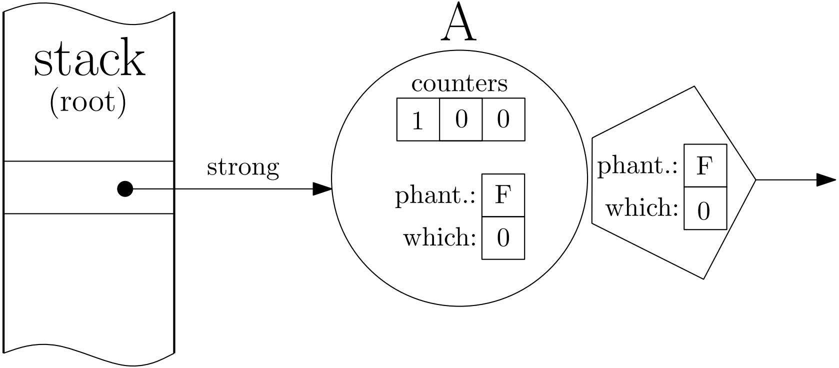

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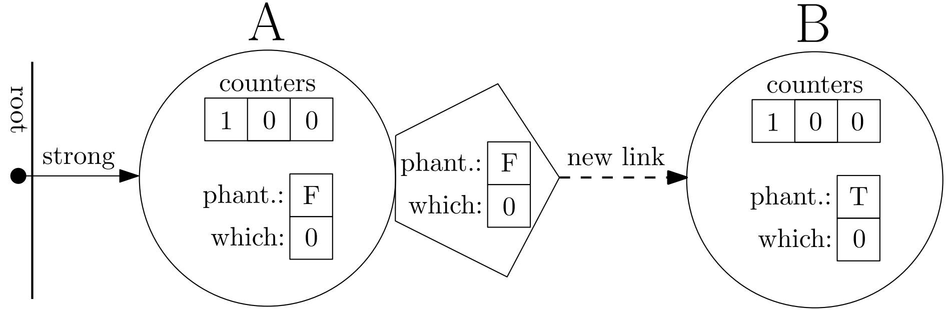

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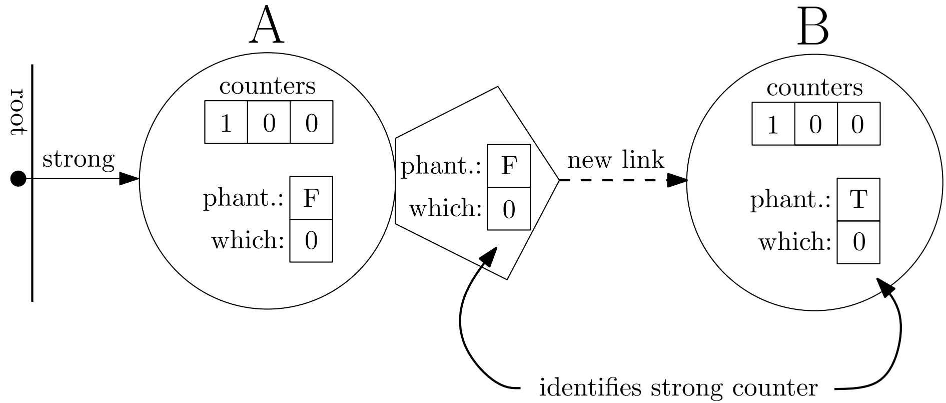

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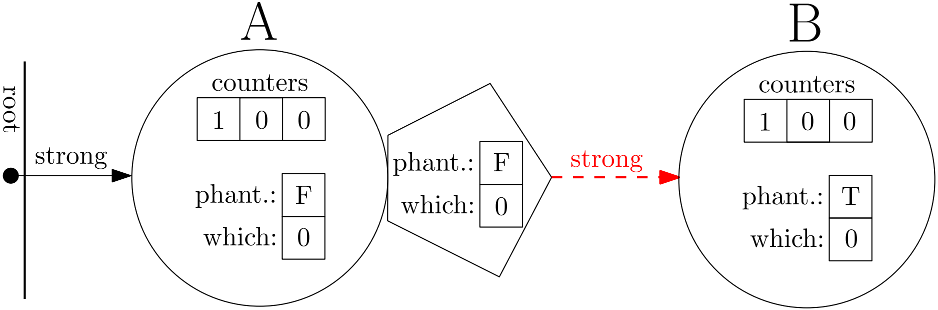

A strong link from A to B is created iff

- The only strong links to A are from roots.
- Object B has no outgoing links.
- Object B is phantomized, and A is not.

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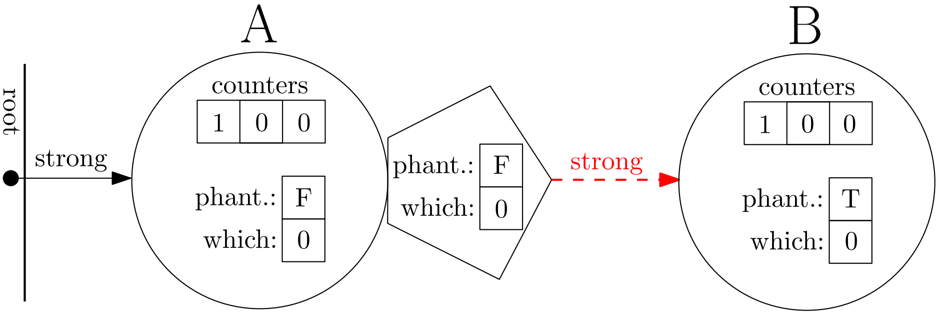

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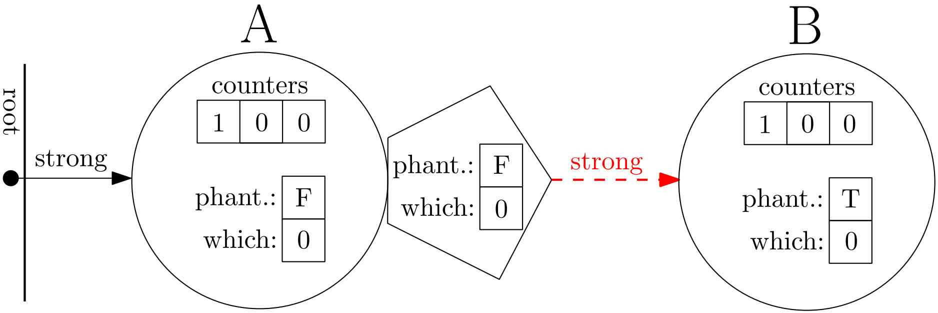

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    - If the weak count is positive, then a sequence of three phases is initiated:
        - Phantomization
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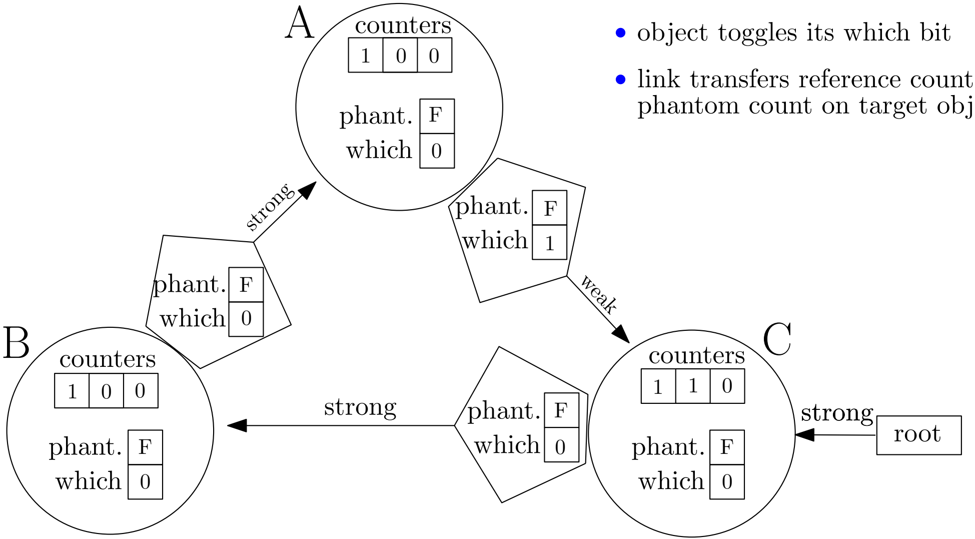
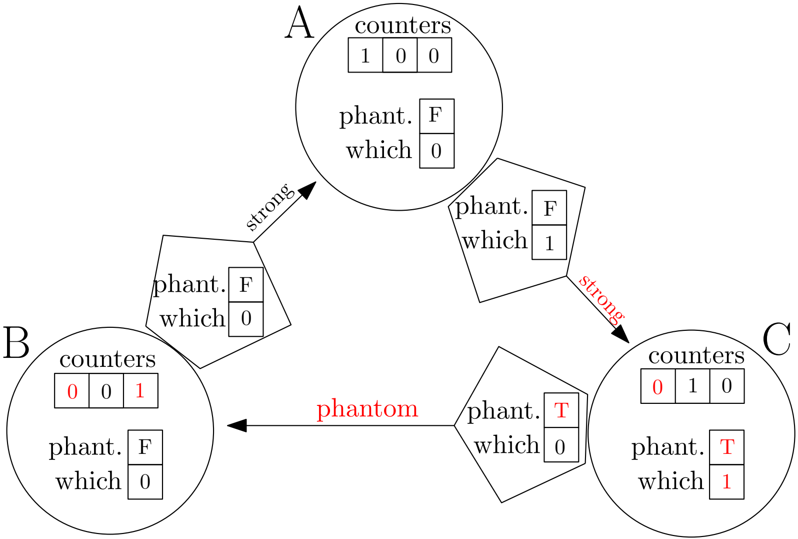


- object toggles its which bit
- link transfers reference count to phantom count on target object

Phantomization



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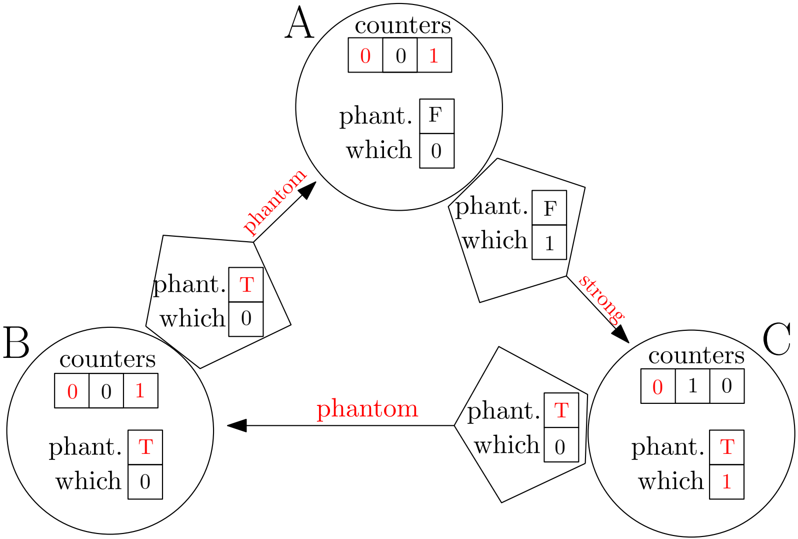

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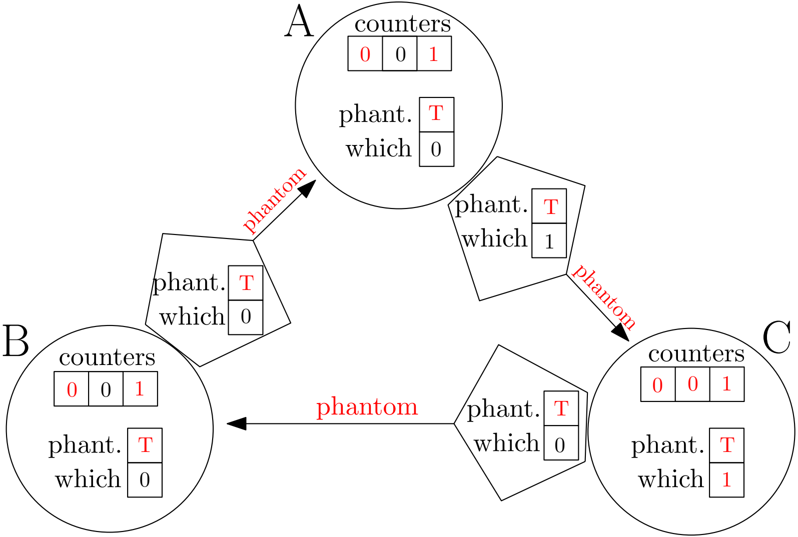

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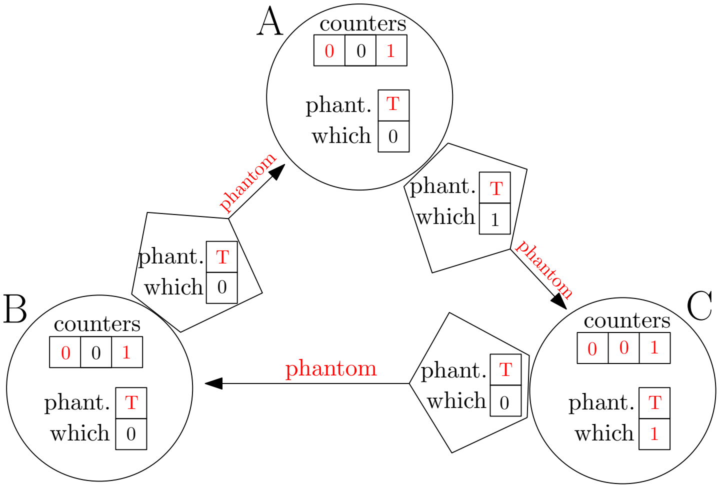

- all objects which recover a positive strong reference count are stored into a recovery list.

Recovery and Cleanup

Recovery

- For each object in the recovery list which has a positive strong reference count:
  - Set phantomized boolean to false
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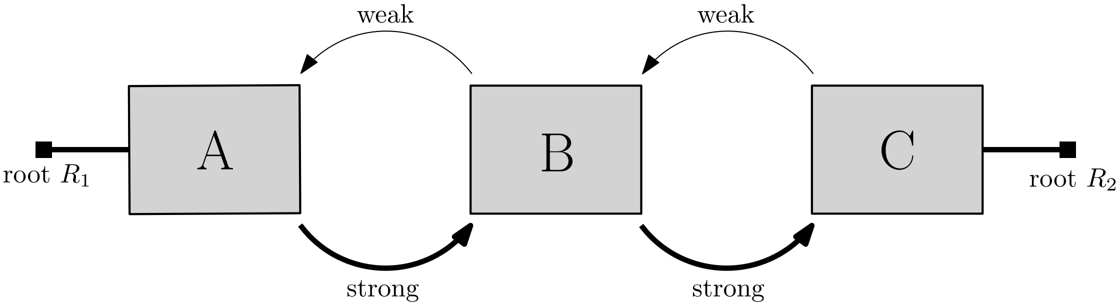

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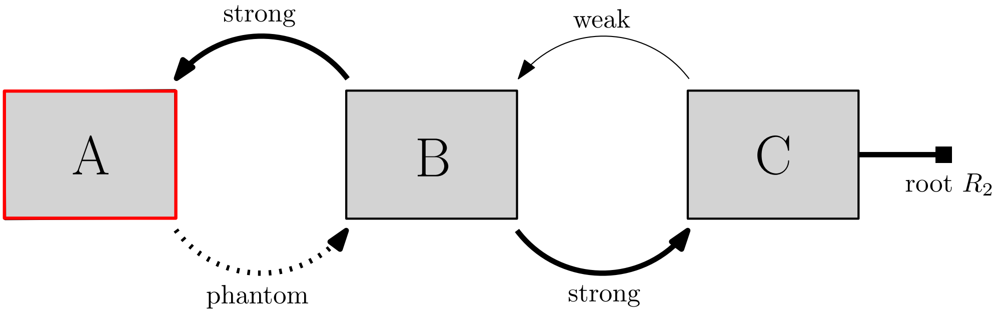

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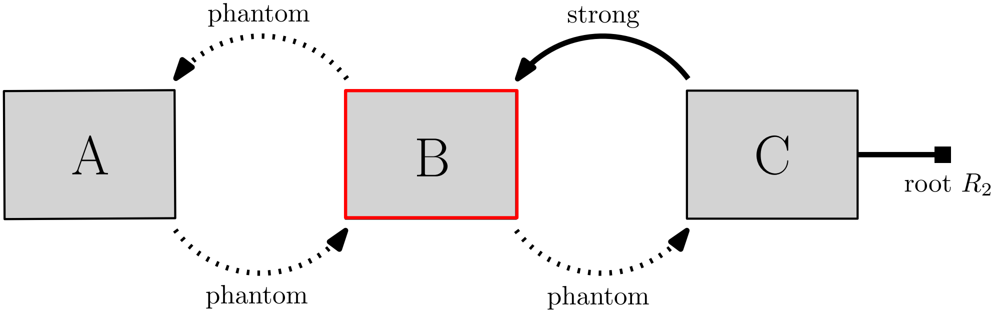
DOUBLY-LINKED-LIST EXAMPLE



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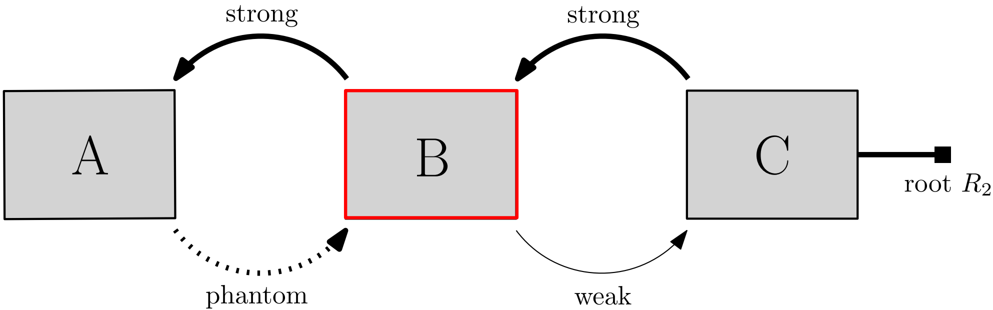

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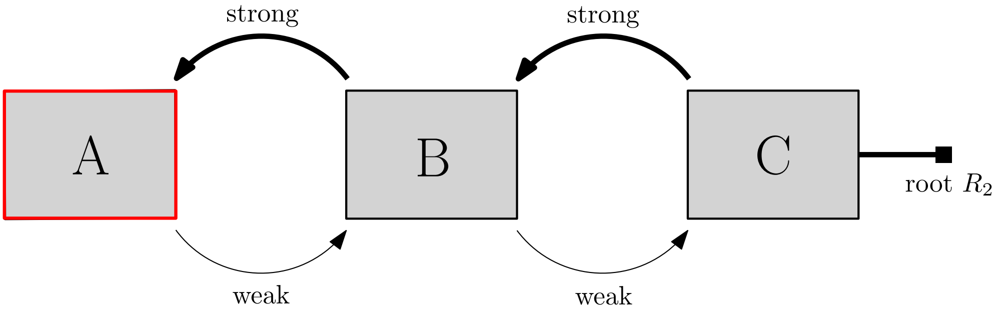

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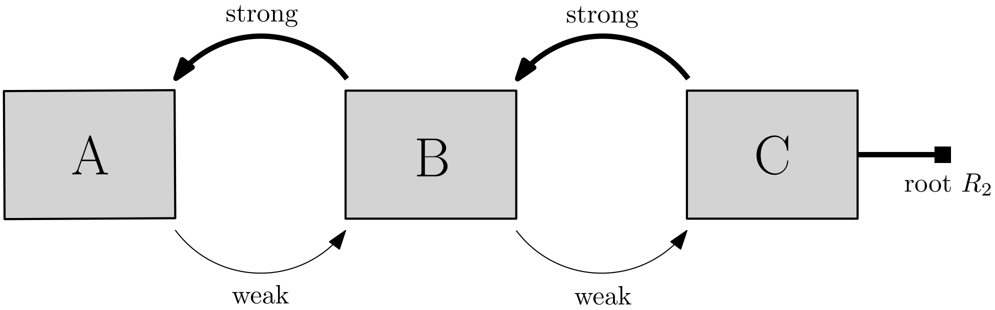

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One Single-Threaded Collector.

- Constraints: phantomization, recovery and cleanup have to run in-order and to completion.
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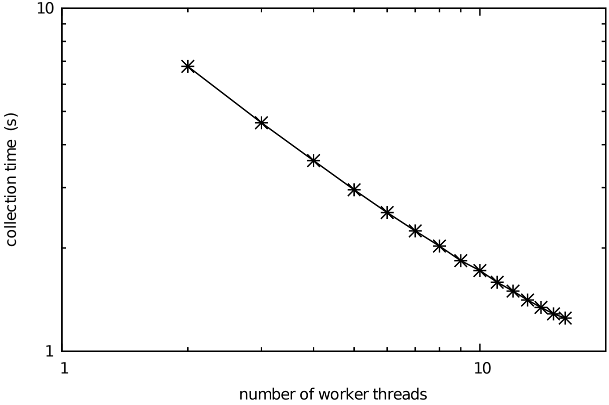

- A large number of independent rings are collected by various number of worker threads.

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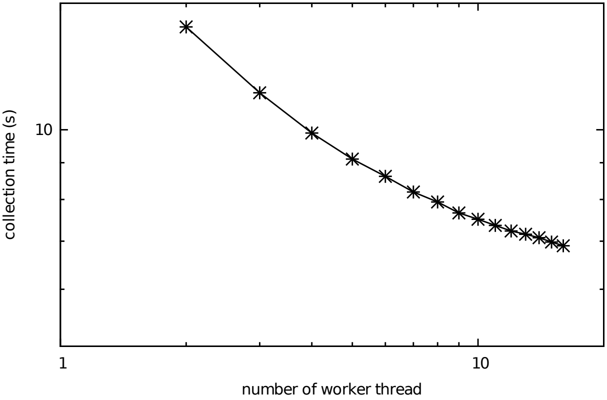

- A chain of linked cycles is created in memory. The connections are severed, then the roots are removed. Multiple collector threads are created and operations partially overlap.

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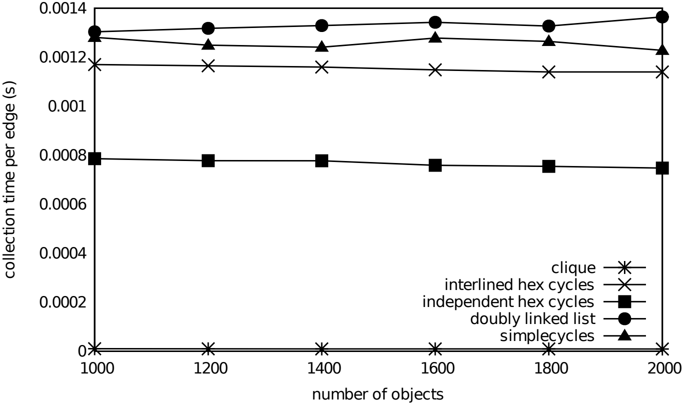

- Graphs of different types are created at various sizes in memory, including cliques, chains of cycles, large cycles, and large doubly linked lists.

Conclusion

Advantages

- Can run at the same time as live system, using multiple threads if desired.
- No need to “stop the world”.
- Performs nontrivial work only when the last strong link is removed.
- When objects do need to be collected, the collector only needs to trace the cycle twice.
- The collector does not need or use back-pointers.
- Useful for distributed systems.

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- No optimized implementation yet.

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- Brownbridge, David R. "Cyclic Reference Counting for Combinator Machines". In: *Record of the 1985 Conference on Functional Programming and Computer Architecture*. Ed. by Jean-Pierre Jouannaud. Vol. 201. Nancy, France, Sept. 1985, pp. 273–288.
- Brandt, Steven R. et al. "Concurrent, Parallel Garbage Collection in Linear Time". In: *Proceedings of the 2014 International Symposium on Memory Management*. ISMM '14. Edinburgh, United Kingdom: ACM, 2014, pp. 47–58. ISBN: 978-1-4503-2921-7. DOI: 10.1145/2602988.2602990. URL: http://doi.acm.org/10.1145/2602988.2602990.