Structural Information in Distributed Computing

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HDR defense
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Distributed systems

Several computing entities cooperating in the absence of a central controller

Various examples

- Computer networks (over the Internet typically)
  Routers / P2P systems / GAFA
- Multi-core processors
- Internet of Things / Sensor networks
- Software agents
- Robots in environments not accessible by humans
- ...

Heterogeneity in size, power, communication mechanisms...

Distributed Computing

What tasks / problems can be solved by several cooperating computing entities despite some constraints:

- Different and partial perceptions of the environment
- Constrained communication
- Asynchrony
- Failures
- Dynamicity
- ...

Differences with parallelism

As usually expressed by Michel Raynal

- Parallelism: provides Efficiency
- Distributed Computing: masters Uncertainty

The multiplicity of computing entities is rather

- a choice in Parallelism
- a constraint in Distributed Computing

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Models

Huge variety of possible assumptions

- Shared memory / Message passing
- Synchronous / Asynchronous
- Anonymous / with IDs
- Reliable nodes / Crashes / Malicious nodes
- Messages: reliable / omission / duplication / reordering / alteration
- ...

Two main points of view

From Pierre Fraigniaud's PODC 2010 invited talk

Time-oriented Dist. Comp.

- Asynchrony
- Failures (typically crashes)
- Direct communication (usually Shared memory)
- Usual goal: Computability

Space-oriented Dist. Comp.

- Communication network (usually Message passing)
- No failures
- Usual goal: efficiency

Distributed computing landscape

Message adversaries

Dynamic networks

Asynchronous
Fault-prone
Direct comm

Comm. network
Fault-free

Self-stabilization

Mobile agents

Distributed computing landscape

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My work

Self-stabilization

Mobile agents

Outline

My contributions

Usual focus

Impact of the information available to the computing entities

- A priori global knowledge
- Knowledge about the future in dynamic networks
- Information from various sensors
- Space complexity

Supervision

- Evangelos Bampas (postdoc) on mobile agents
- Christian Glacet (PhD) on routing
- Ahmed Wade (PhD) on dynamic networks
- Antonin Lentz (PhD) on multi-criteria shortest-paths

Moving and Computing

The computing entities are mobile (controlled mobility)

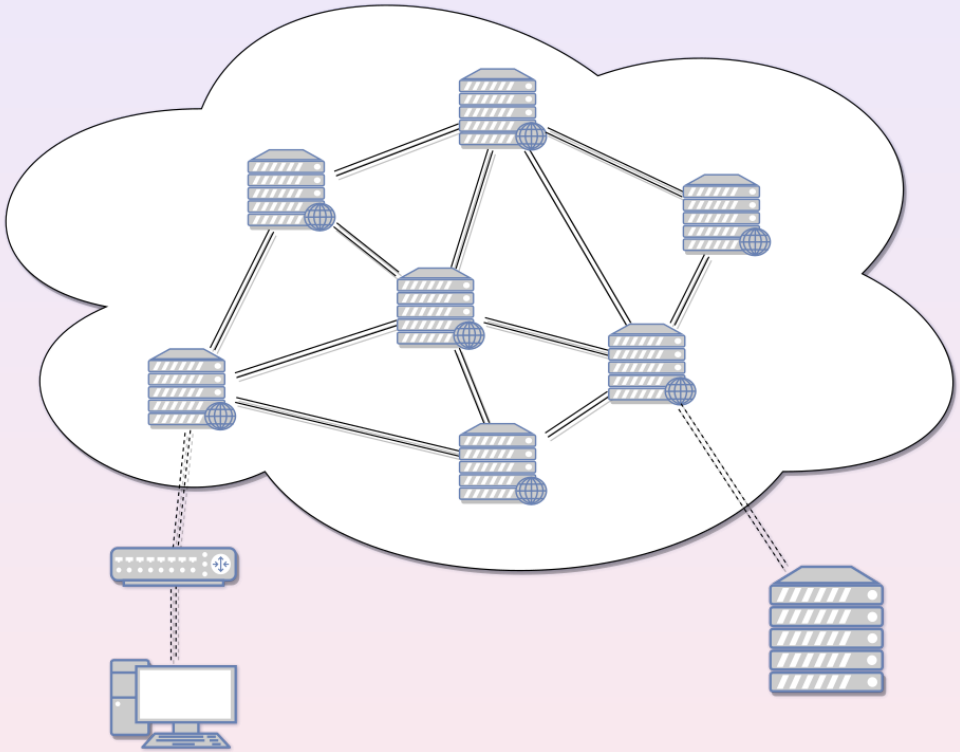
Agents

- Operating in a network
- Can move from node to node through the edges
- Local view (just the current node)

Robots

- Global view of the environment
- Operating in a generally continuous environment

On routing



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Routing scheme

- Routing tables
- Message/packet headers
- Routing algorithm

Issue: routing tables grow faster than the memory

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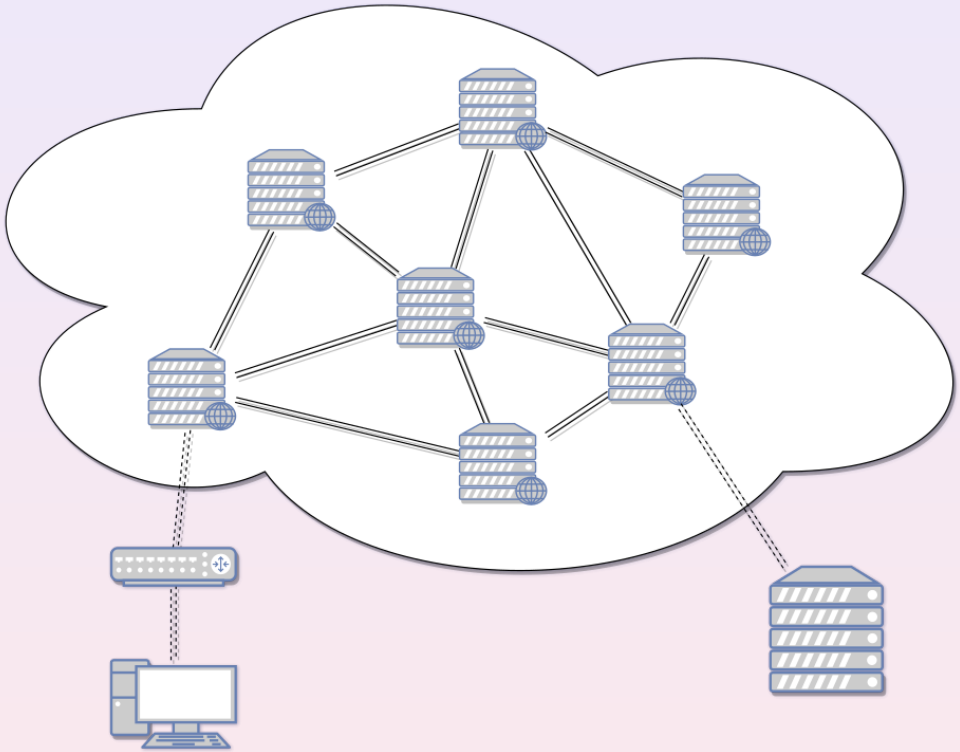

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One result about routing
(cf. Christian Glacet's PhD thesis)

[Gavoille, Glacet, Hanusse, I. DISC 2013]

Distributed routing scheme for weighted n-node networks

- Asynchronous algorithm (and optimal synchronous time)
- Compact routing tables: $\tilde{O}(\sqrt{n})$ bits
- In "small-world" networks: $\tilde{O}(n^{3/2})$ messages
- Stretch ≤ 5 (multiplicative overhead on the path length)

Although shortest-path routing implies

- Routing tables of $\tilde{\Omega}(n)$ bits
- $\tilde{\Omega}(n^2)$ messages (even in "small-world" networks)

Context on dynamic networks

Distributed computing systems are becoming more and more dynamic.

Causes

- Frequent connections / disconnections to/in the network
- Fault or crash of communicating objects and links
- Uncontrolled mobility of the computing entities

Classical models: Static fault-tolerant networks

- Assume that the frequency of fault occurrences is small
- Assume that the number of fault occurrences is small

In fact, these models become insufficient for very dynamic networks.

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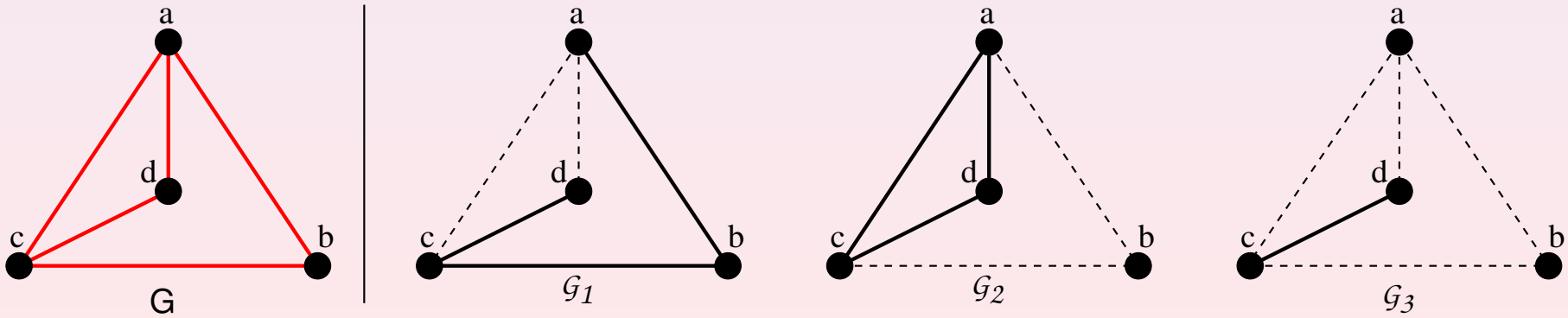
The model we consider

Evolving graphs

- One of the first developed models, and also one of the most standard.
- An evolving graph is a (possibly infinite) sequence $\mathcal{G}_1$, $\mathcal{G}_2$, $\mathcal{G}_3$, ... of static graphs based on the same set of nodes.
- We focus here on constantly connected evolving graphs



Some results about dynamic networks
(cf. Ahmed Wade's PhD thesis)

Exploration of constantly connected evolving graphs with known dynamics

Known results

- Temporal diameter is at most $n - 1$
- $\Longrightarrow$ Exploration time is at most $(n-1)^2$
- Some m-edge base graphs require exploration time $\Omega(m)$

[I., Wade, ToCS, 2018] & [I., Klasing, Wade, SIROCCO 2014]

- Ring: optimal worst-case time $2n - 3$
- Ring: exploration time decreases when stability increases
- Cactus (tree of rings): algorithm with sub-polynomial overhead

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Problem

Black hole in a network

Node blocking and destroying any mobile agent entering it

Motivations:

- Site which is destroyed or dangerous for a physical robot
- Node infected by a "killer" virus
- Mute or crashed node

Black Hole Search

From a safe node (homebase), a team of mobile agents has to locate the black hole(s)

Performance: nb of agents, nb of moves

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(A)synchronous

Synchronous

Agents act simultaneously at every pulse of a global clock

$\Longrightarrow$ Possible to wait for an agent gone exploring a potentially dangerous edge

Asynchronous (our case)

Every action takes a finite but unbounded time

$\Longrightarrow$ A priori impossible to distinguish a very slow link from a link leading to the black hole

$\Longrightarrow$ Useless to wait for an agent

$\Longrightarrow$ Pb equivalent to the exploration of dangerous graphs

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Indirect communication models

Communication/coordination

No direct communication but

Whiteboards (memory space on each node).

or Pointers (mark a specific port).

or Pebbles (node markers, which can be carried by agents).

Related work

Seminal results (asynchronous, whiteboards)

[Dobrev, Flocchini, Prencipe, Santoro. Dist. Comp. 2006]

	nb of agents	nb of moves
No information (besides n)	$\Delta + 1$	$\Theta(n^2)$
Sense of direction	2	$\Theta(n^2)$
Known map	2	$\Theta(n \log n)$

Pointers, ring, FIFO links

[Dobrev, Santoro, Shi. CIAC 2006]

- $O(1)$ pointers in total, up to 3 per node
- Nb of moves : $\Theta(n \log n)$

Pb : Is coordination through pebbles sufficient ?

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Our results

Model

- Arbitrary graphs (known map)
- Links do not need to be FIFO

Optimal result

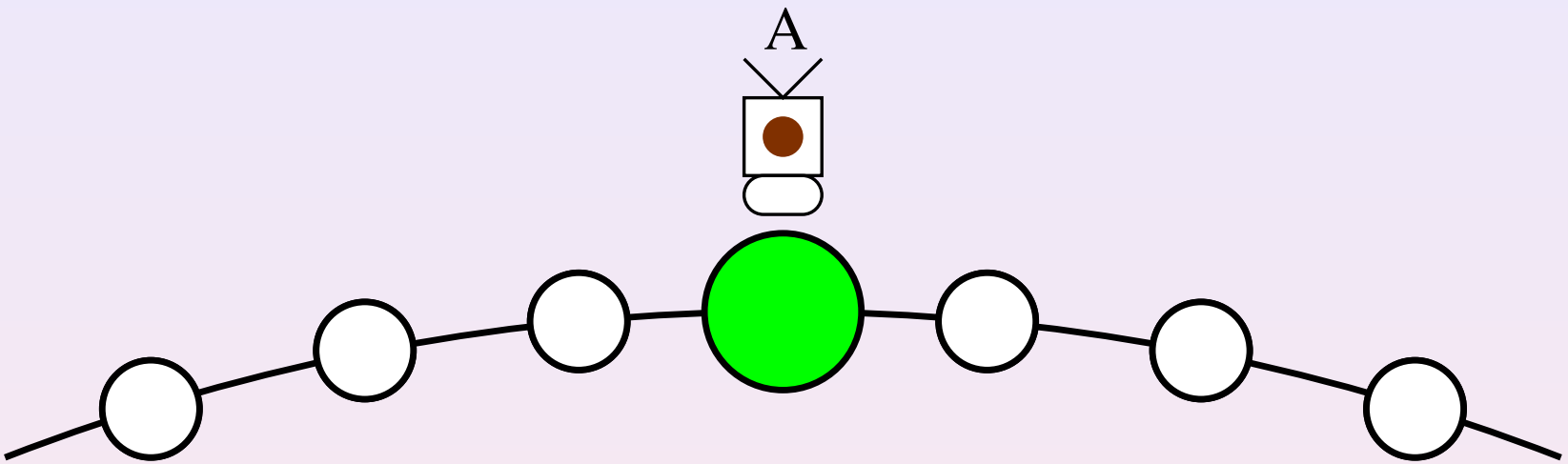
- 1 pebble per agent
- 2 agents
- $\Theta(n \log n)$ moves

Case of the ring

Model

- Two identical agents equipped with one pebble each
- Indistinguishable pebbles
- At most one pebble per node / carried by an agent
- Asynchronous ring with exactly one black hole

First steps

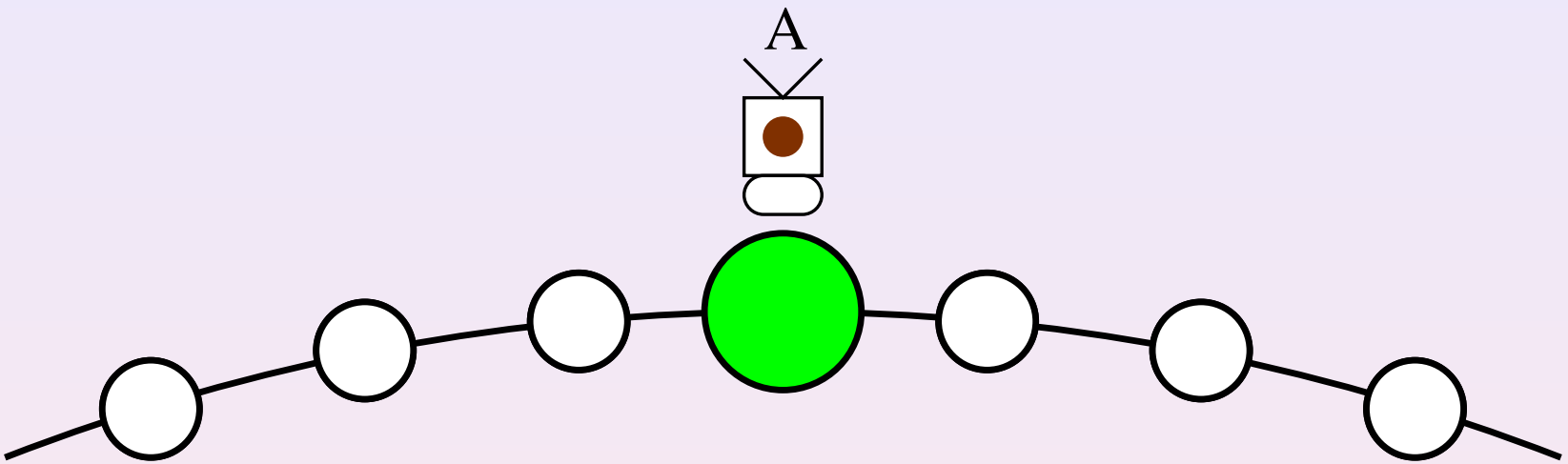


Beginning of the algorithm

If node is empty **then**

Go right

First steps



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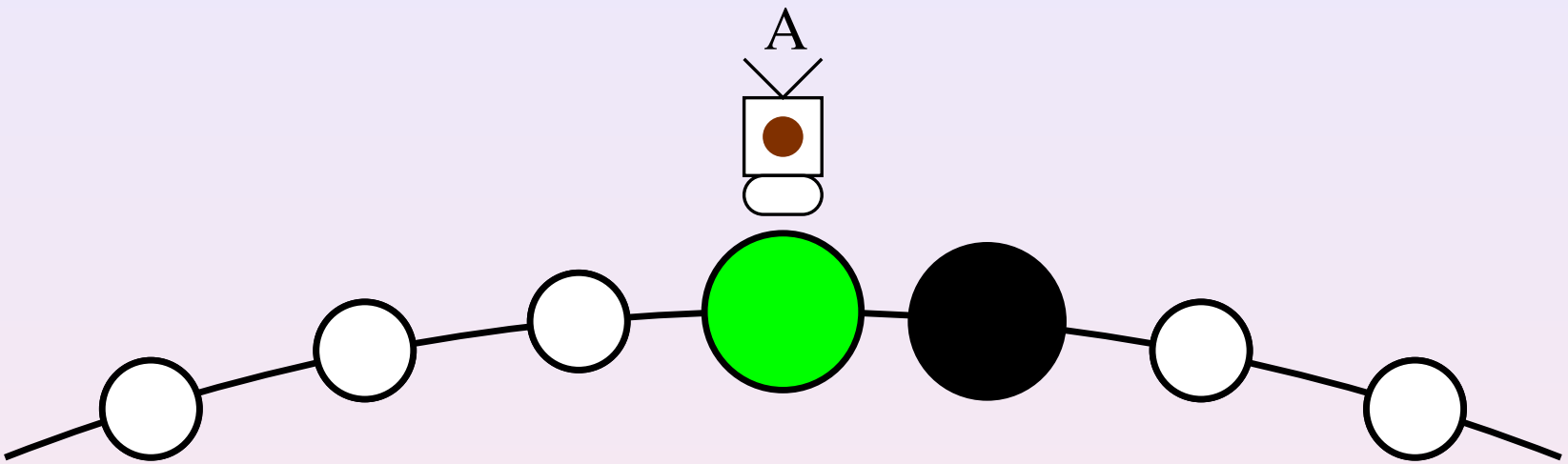

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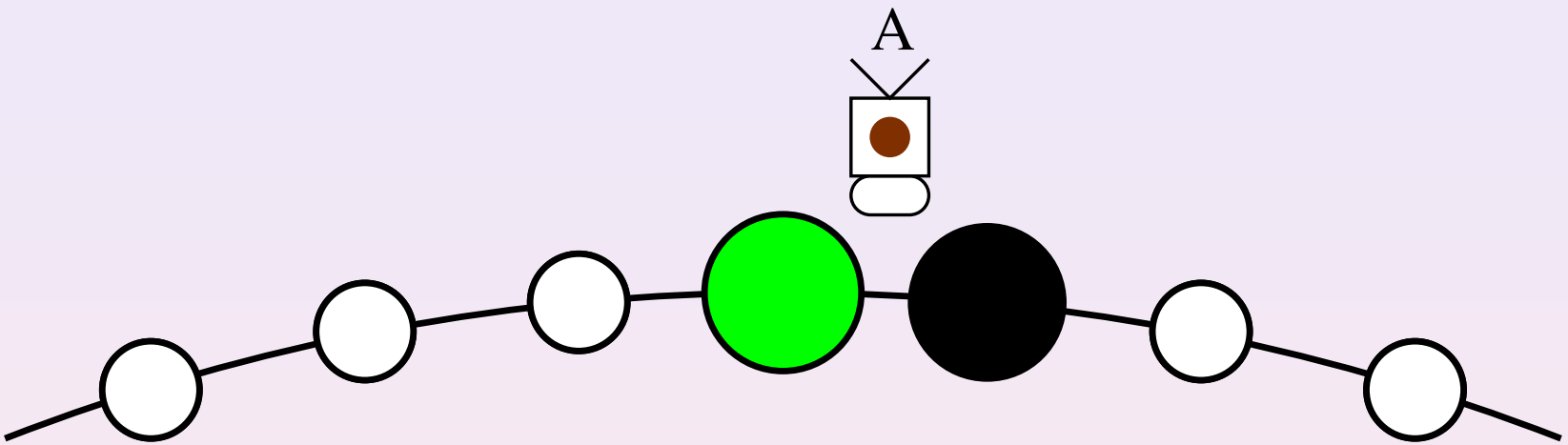

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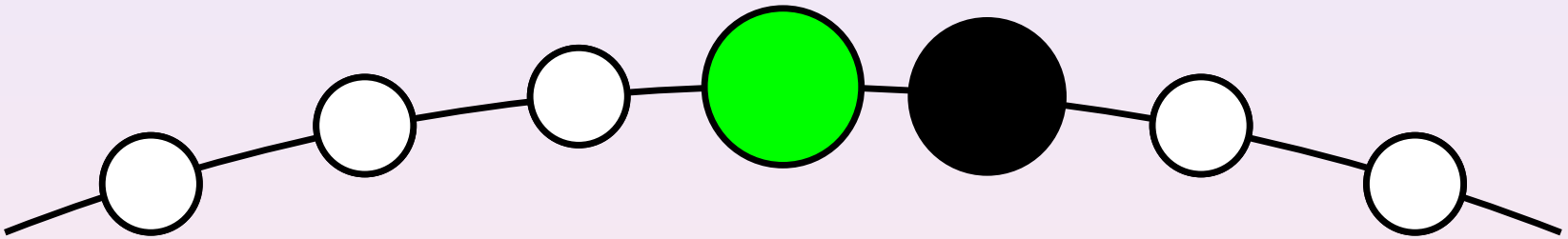

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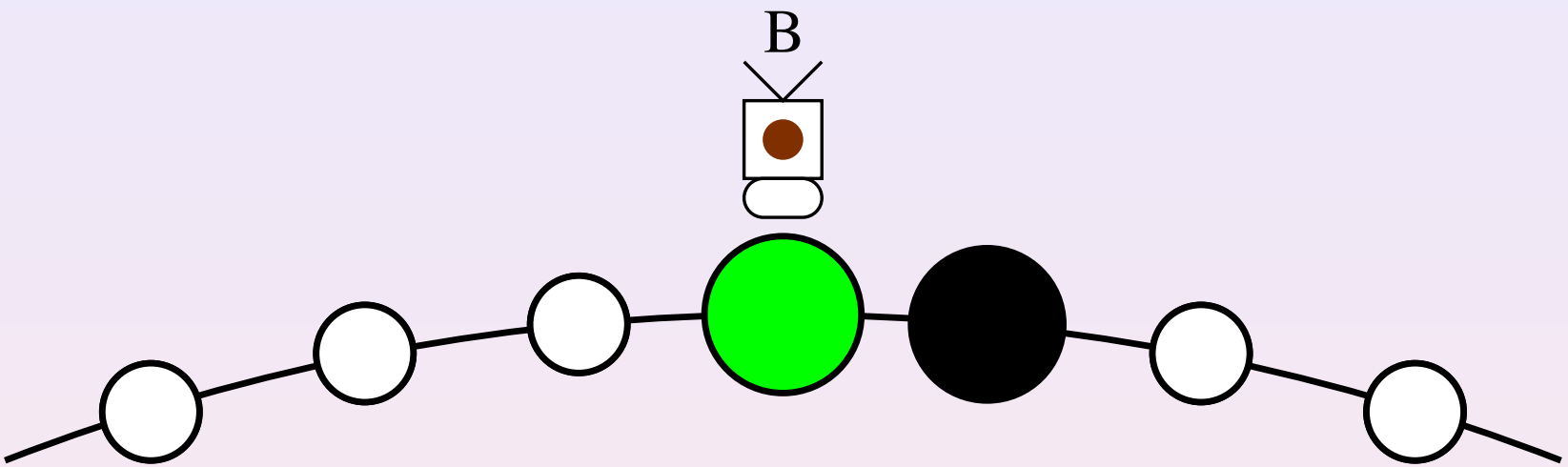

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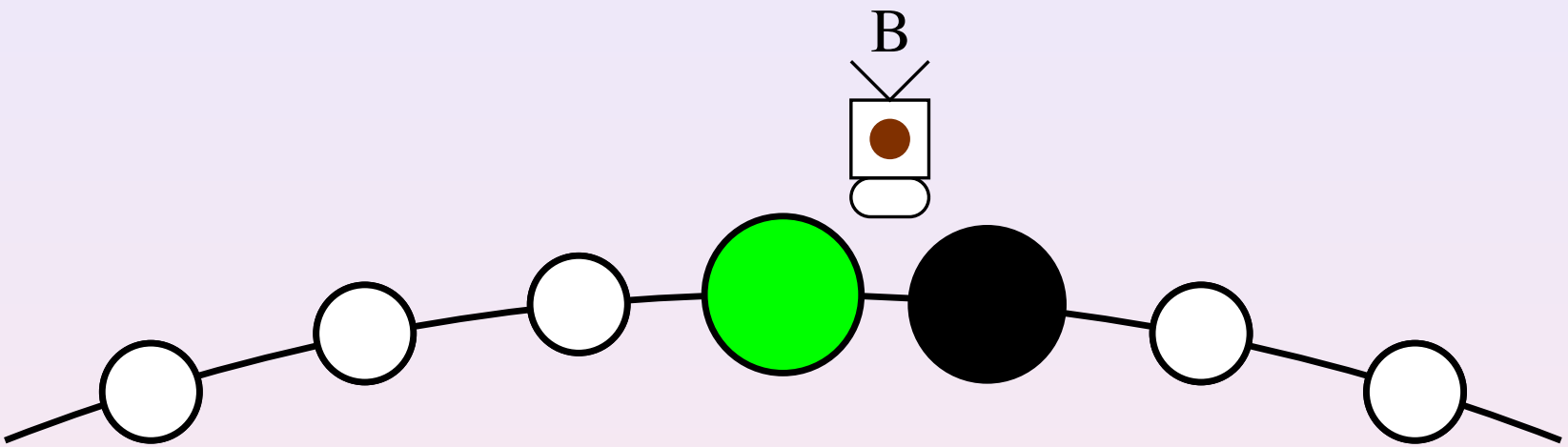

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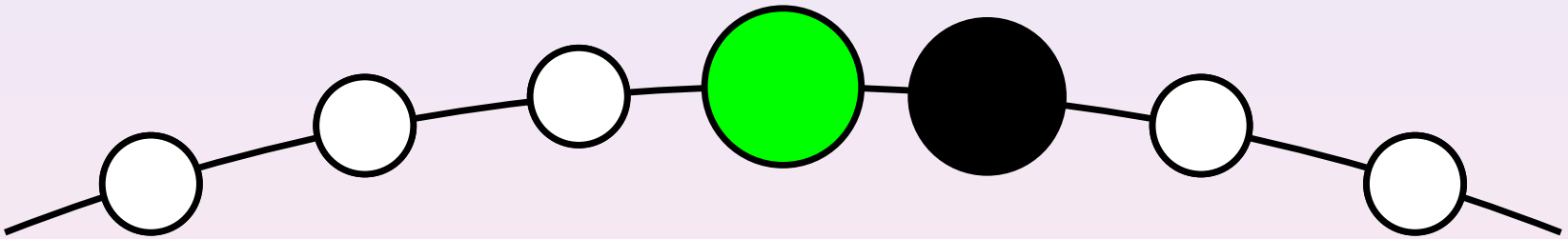

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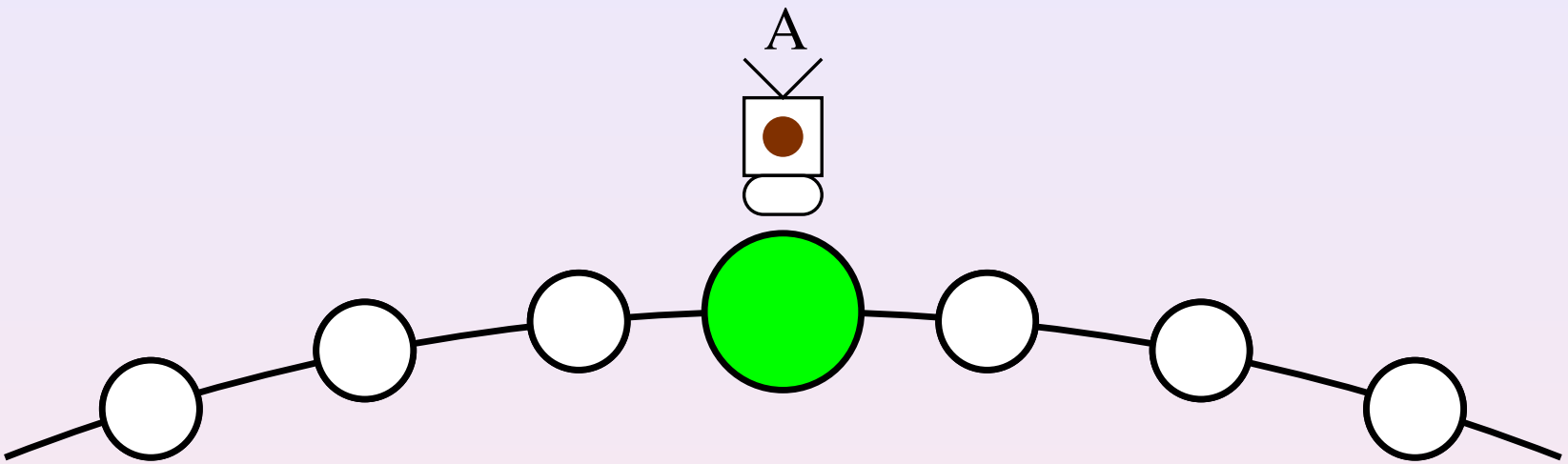

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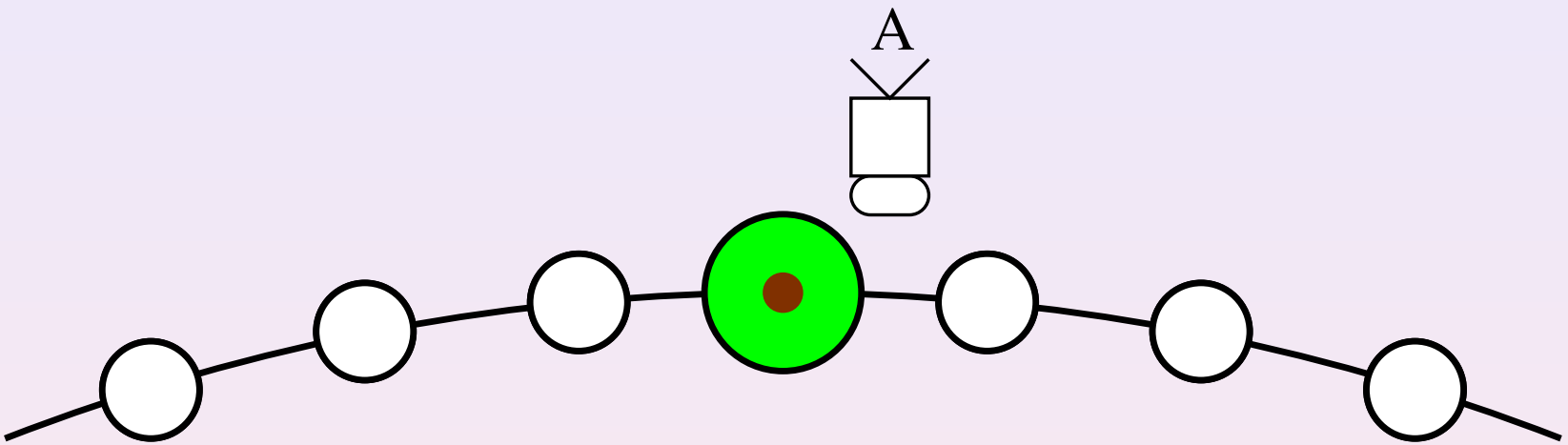

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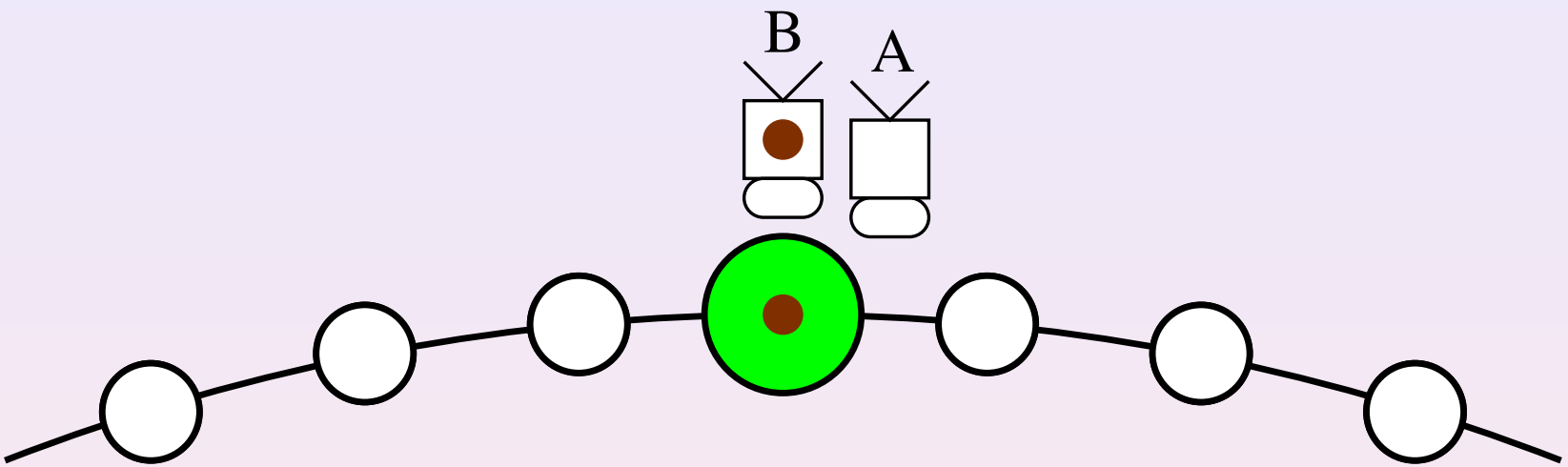

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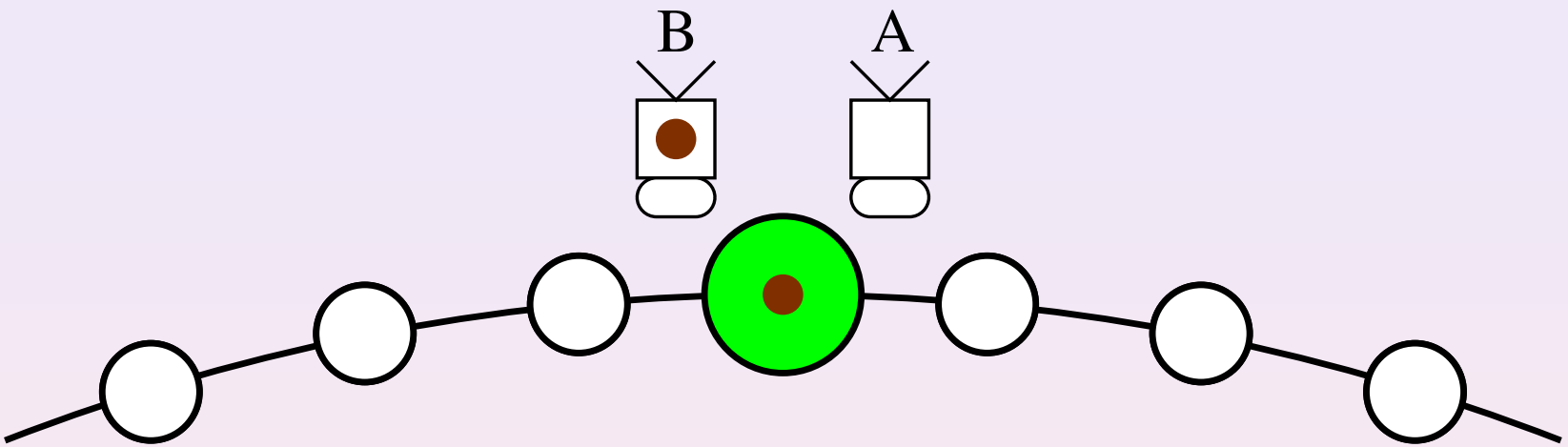

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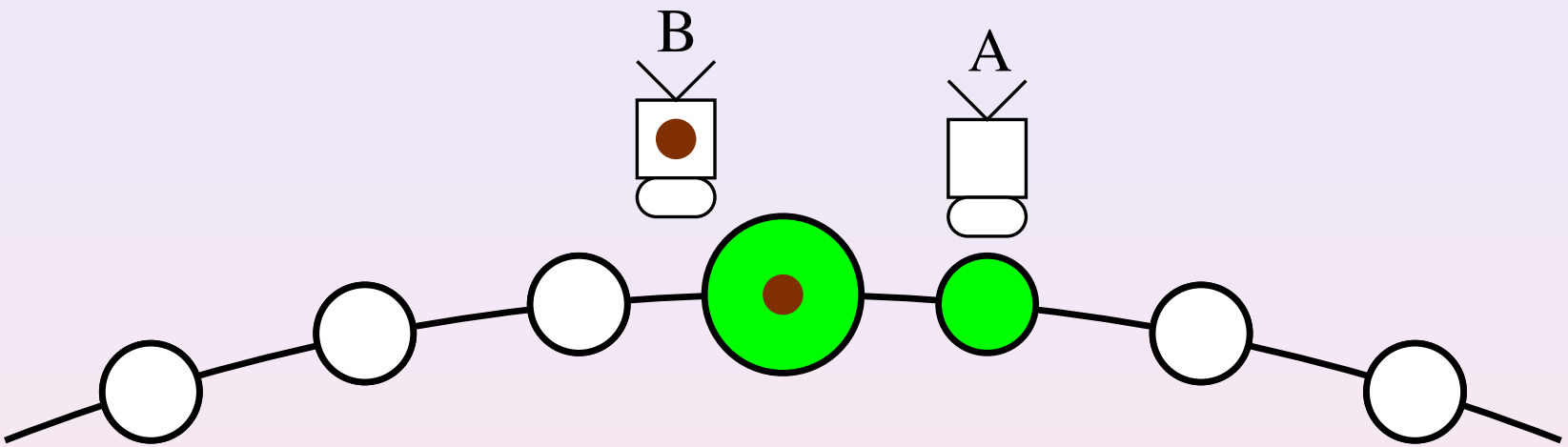

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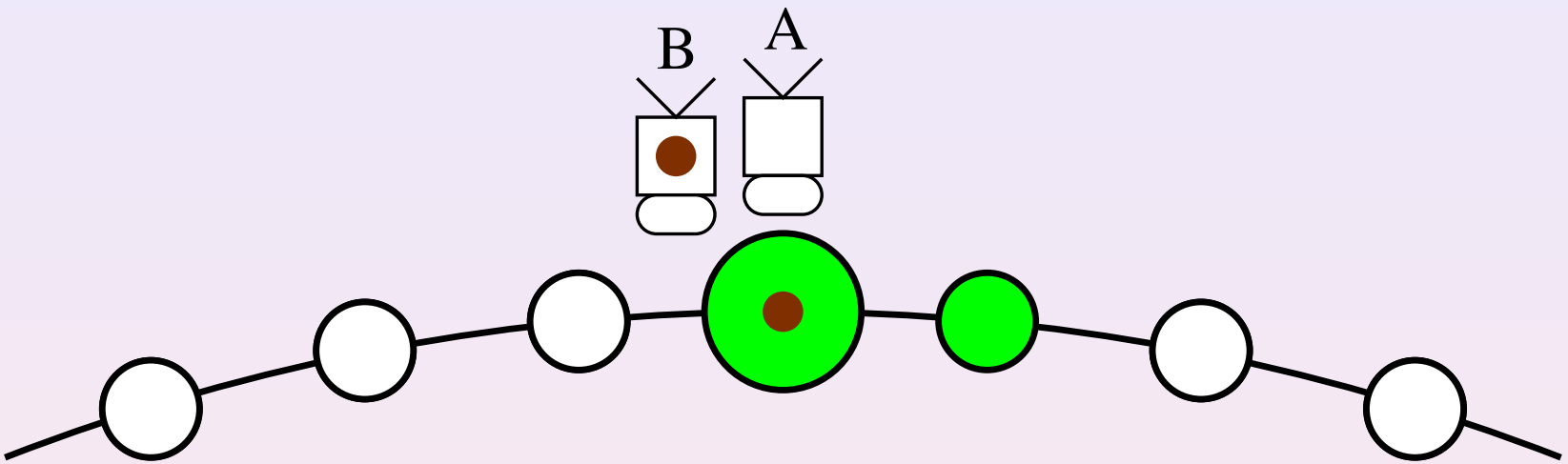

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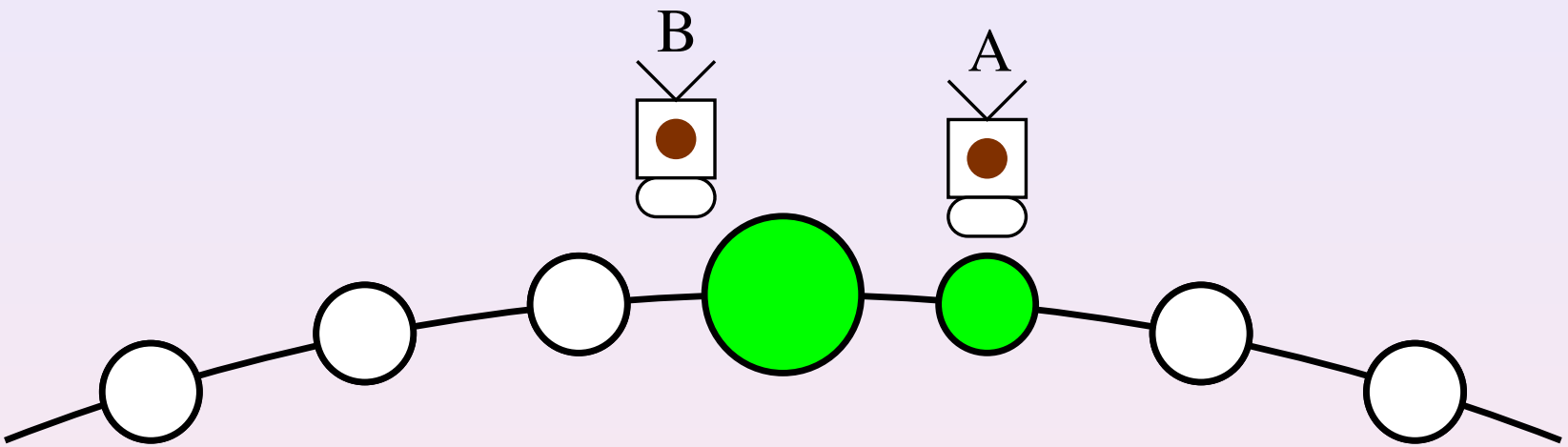

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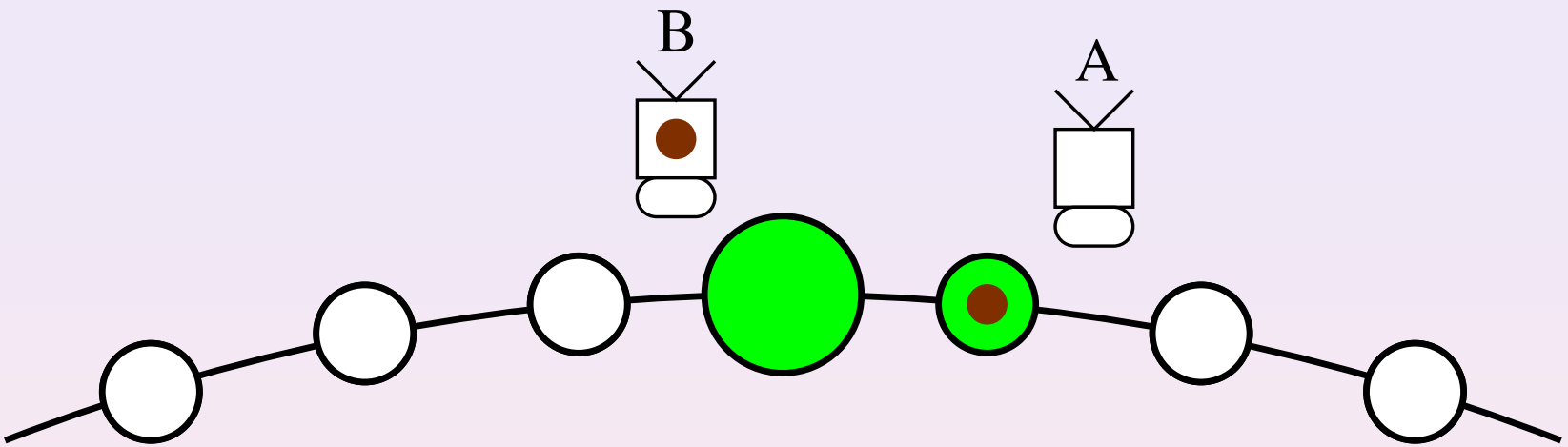

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Cautious walk

Exploration of $e = \{u, v\}$ from u to v

Simple cautious walk

Initially: agent at u with a pebble, node without a pebble

- Put down the pebble (warn the other agent) and go to v
- Come back to u
- Retrieve the pebble and return at v

Double cautious walk

Initially: agent at u with a pebble, node u with a pebble

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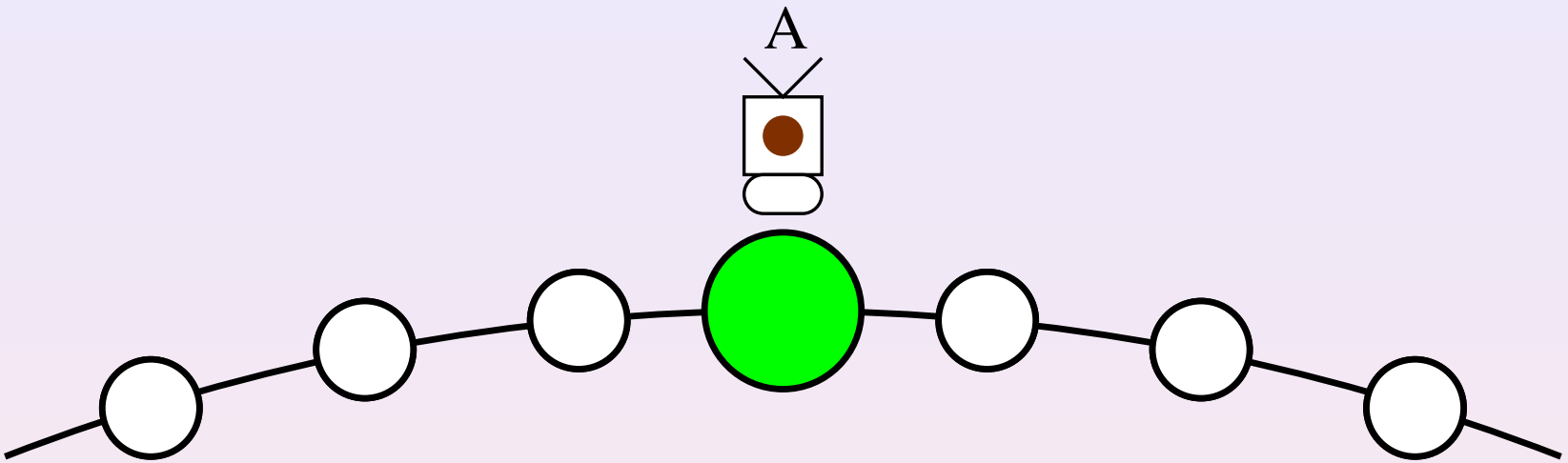

Quick description

If the agent "controls"

- 1 pebble → Simple cautious walk to the right
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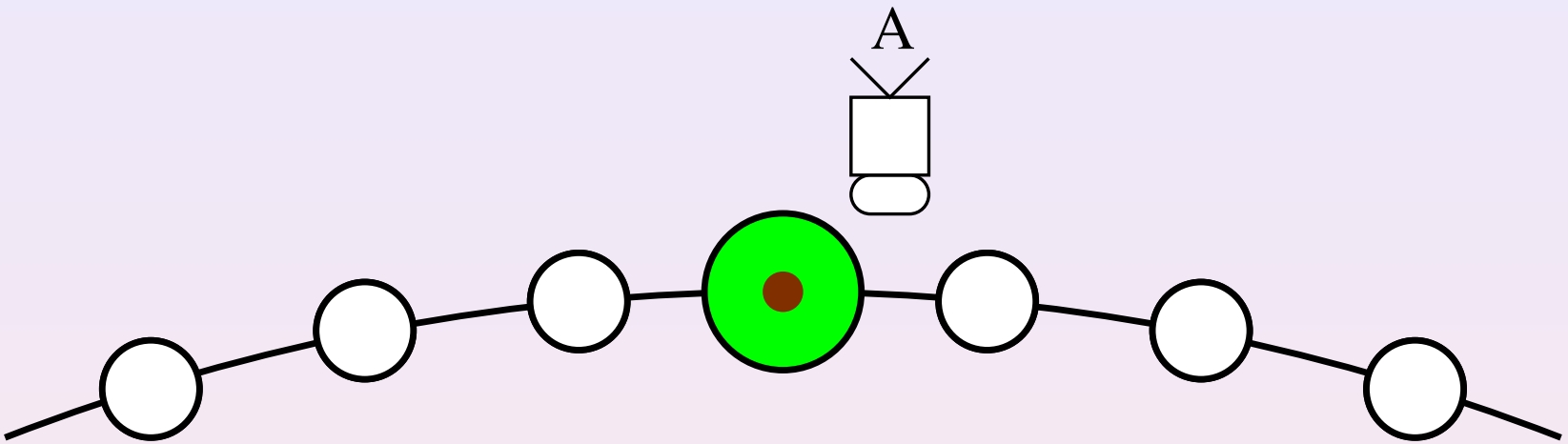

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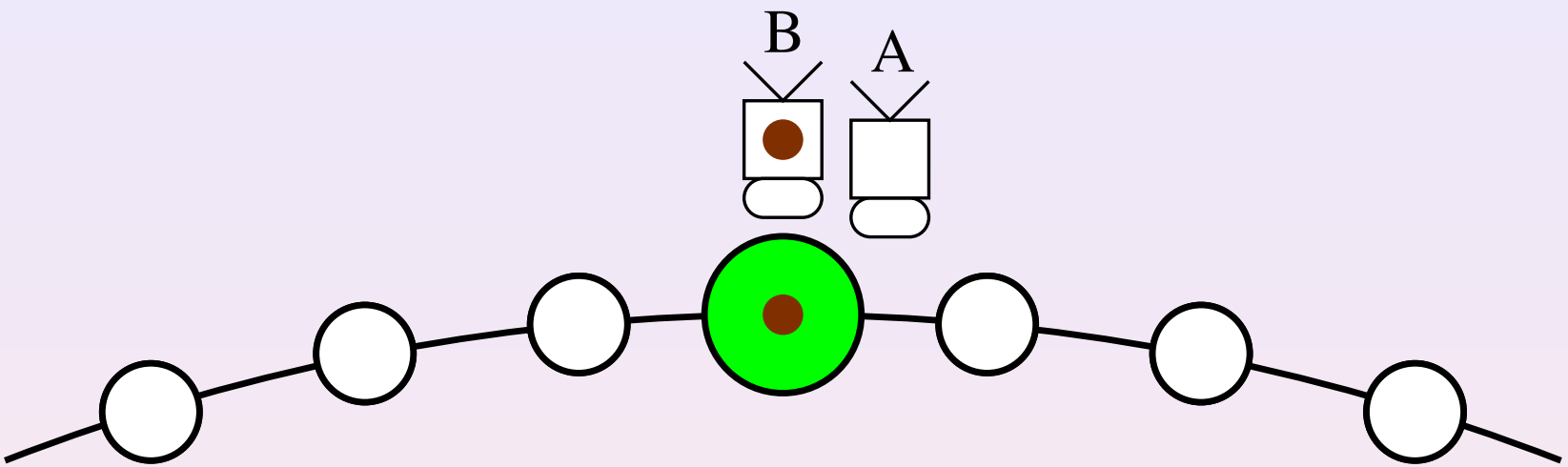

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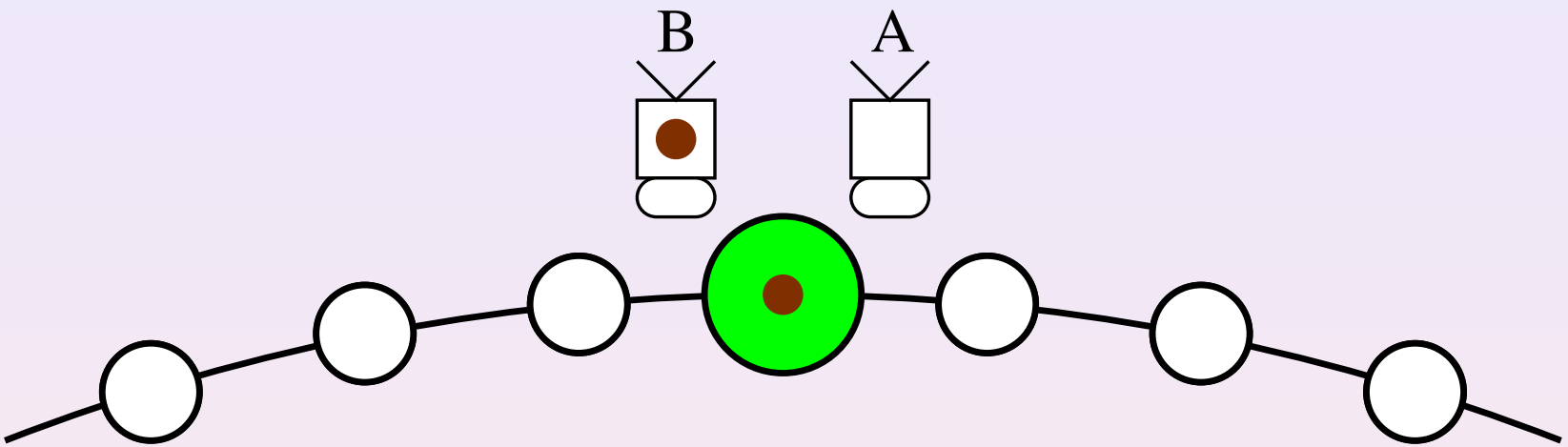

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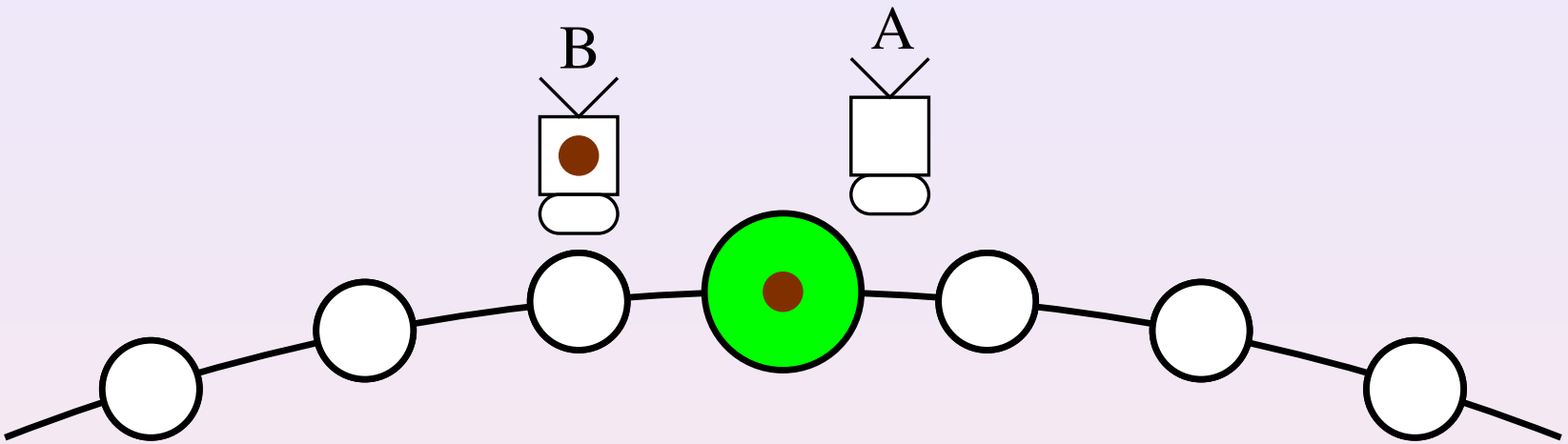

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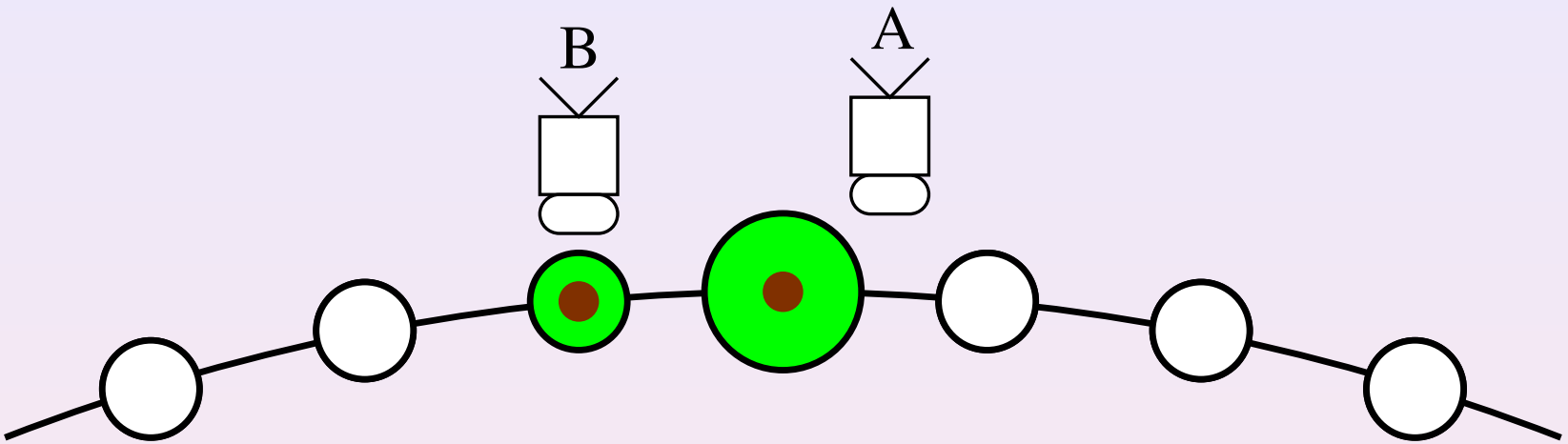

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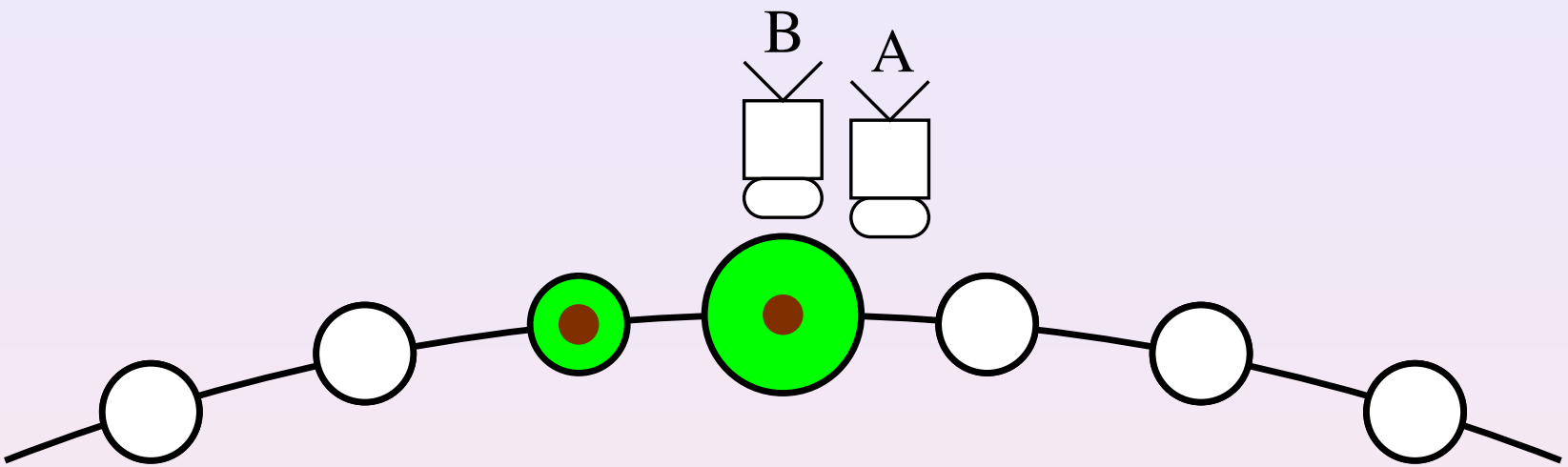

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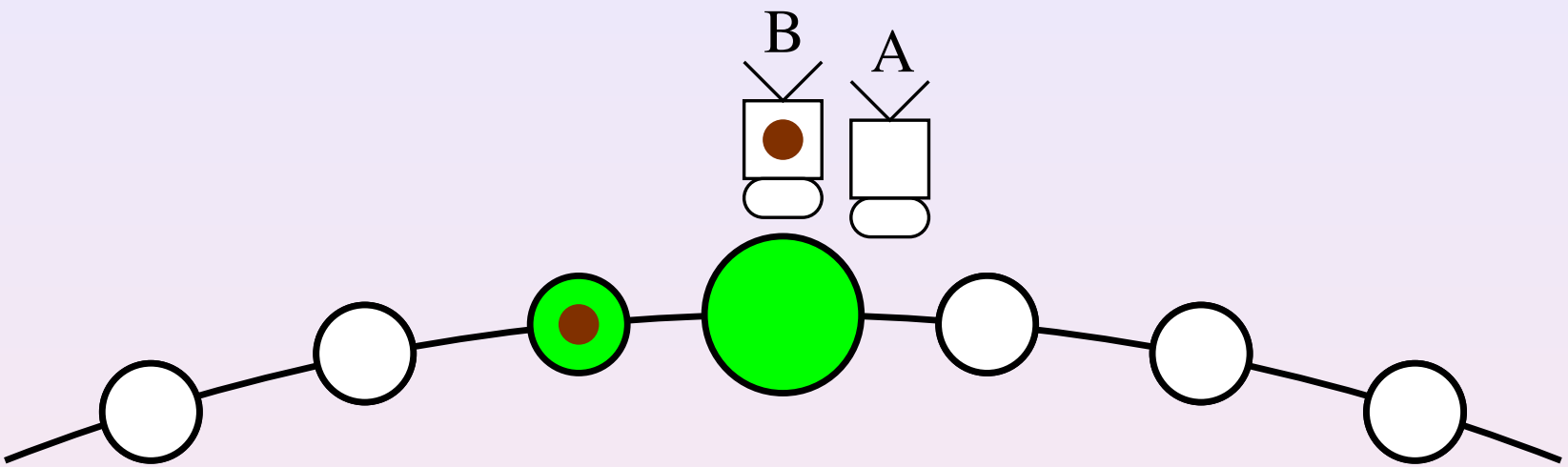

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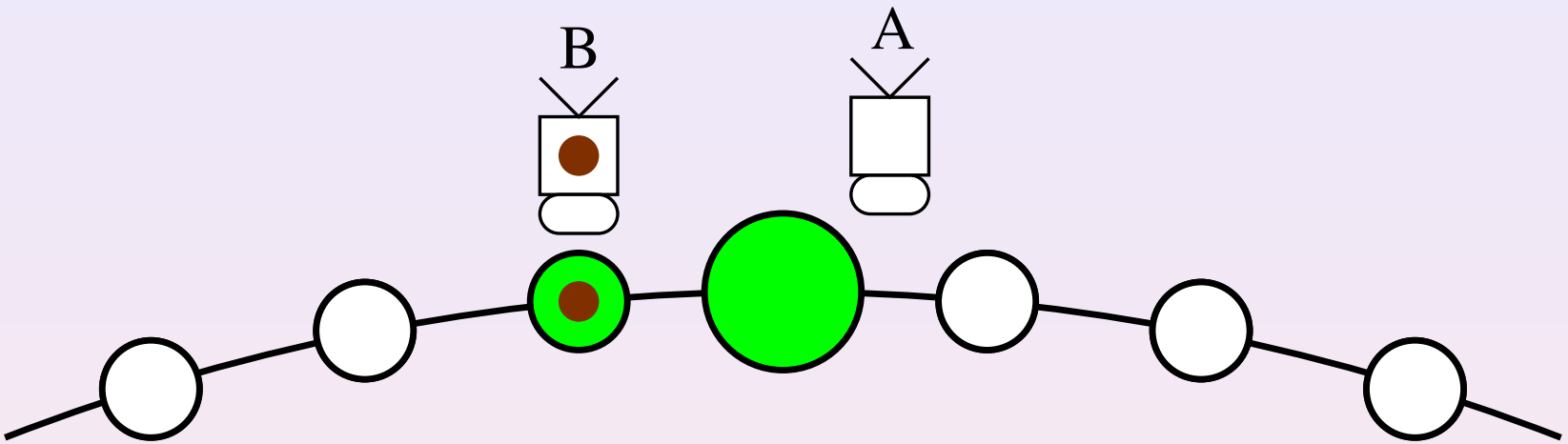

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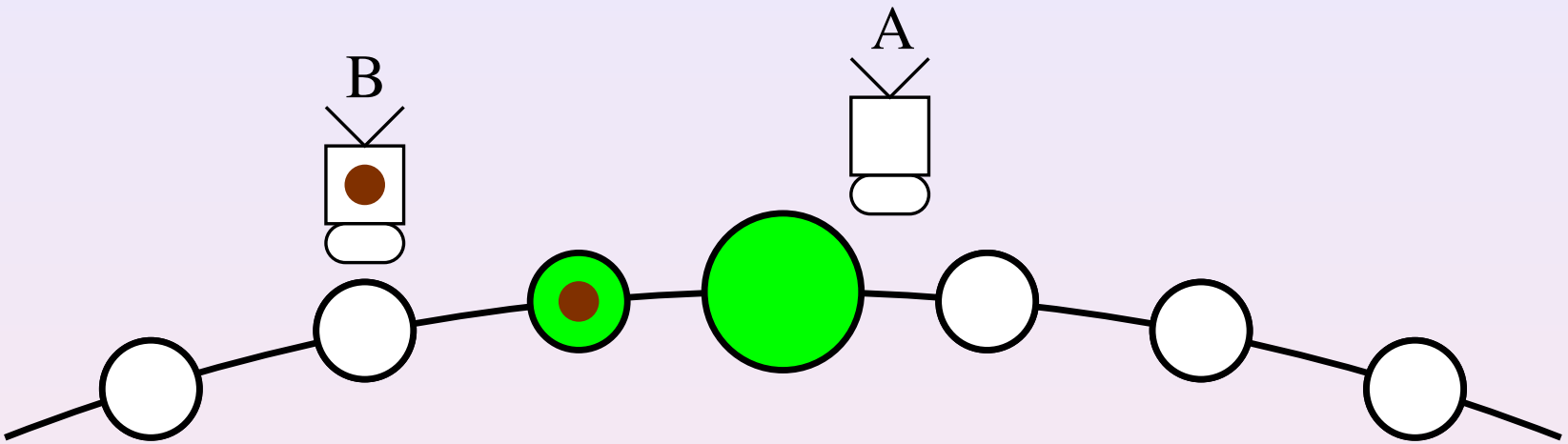

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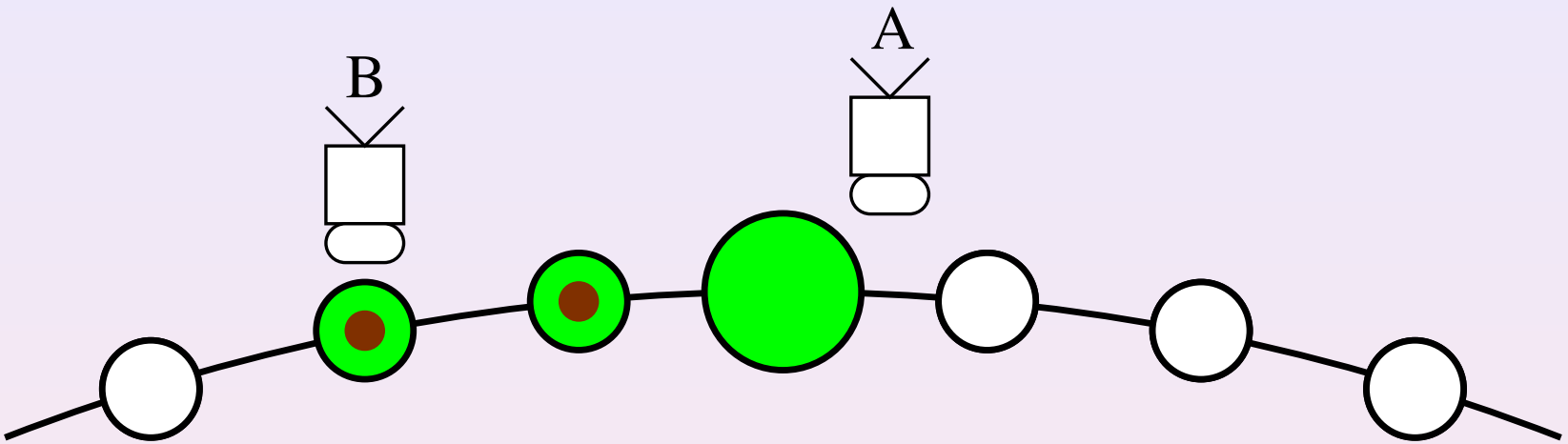

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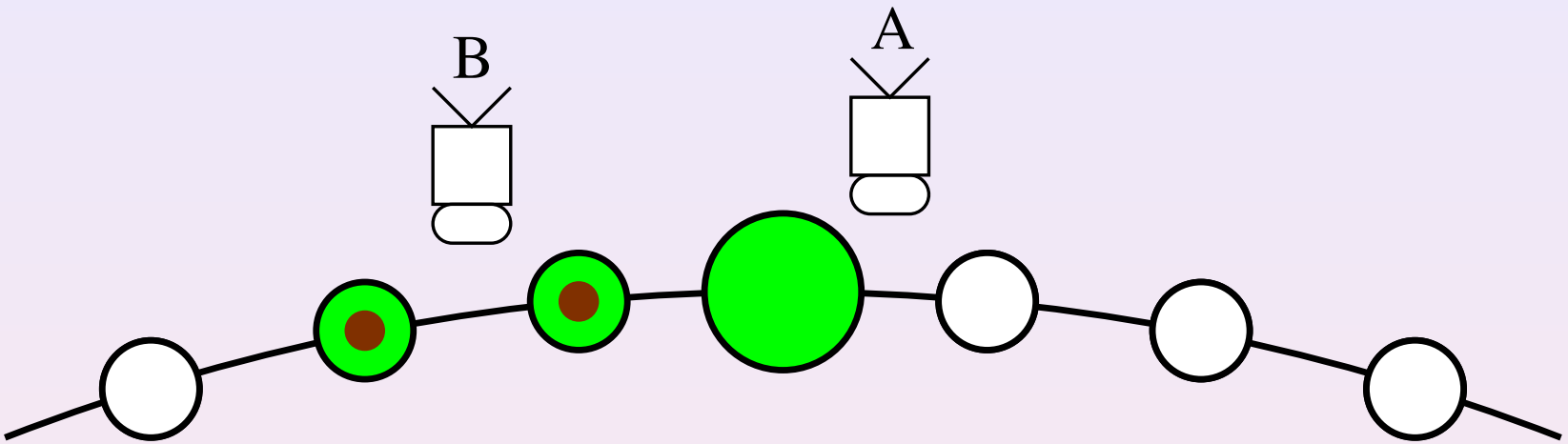

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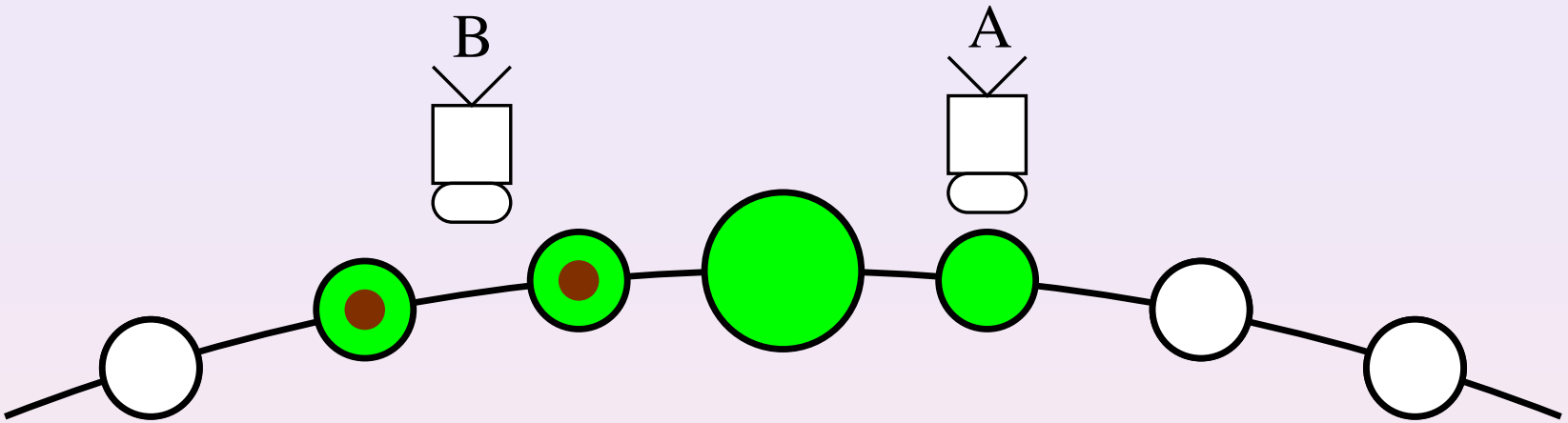

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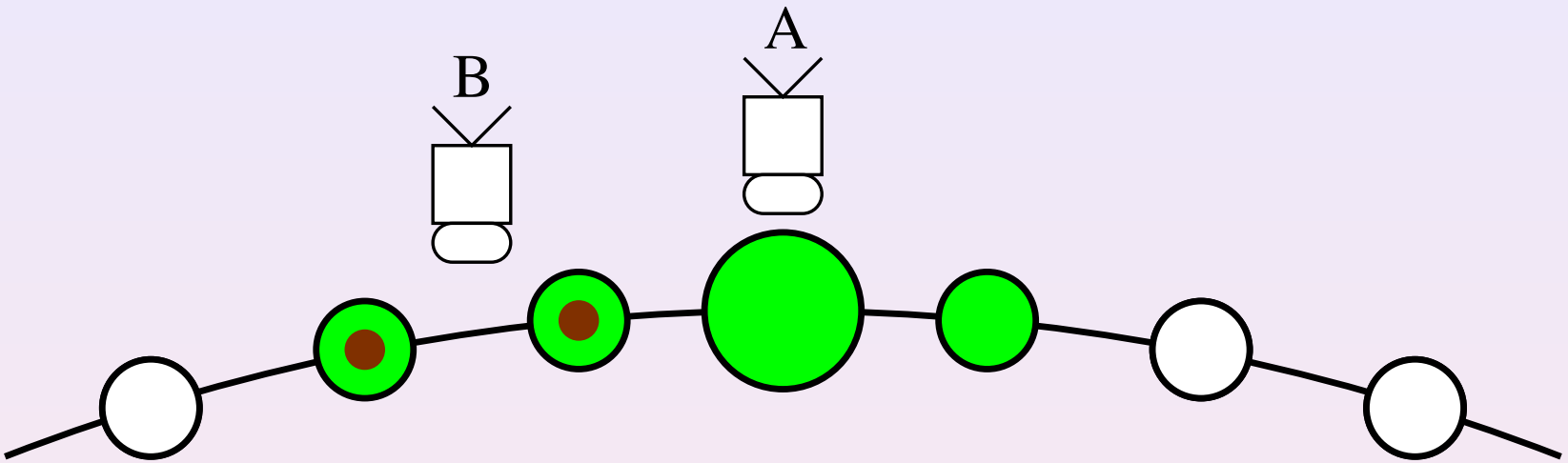

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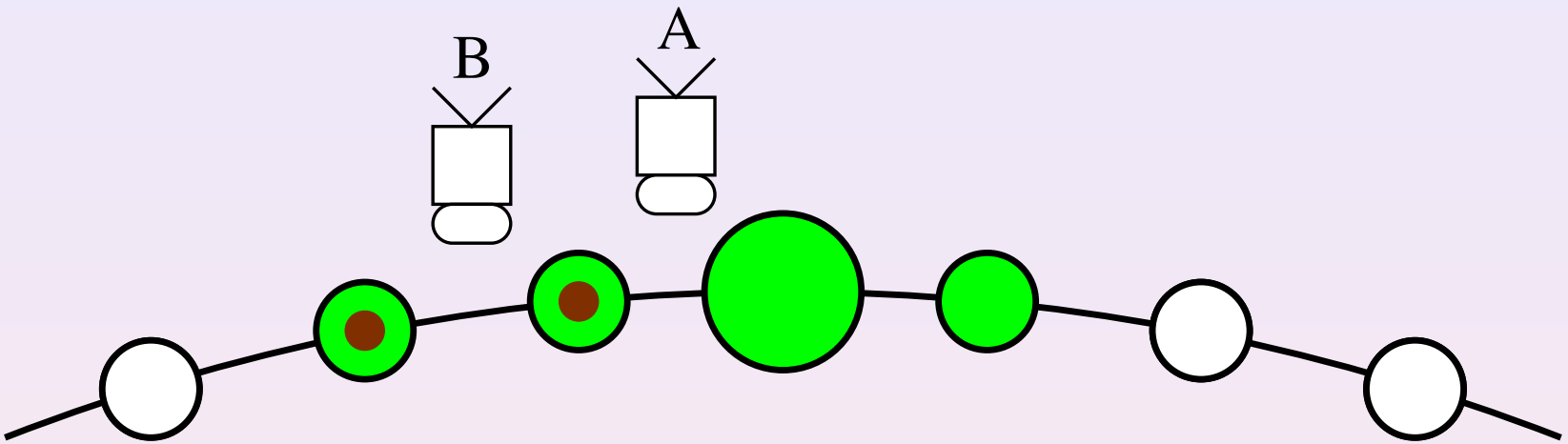

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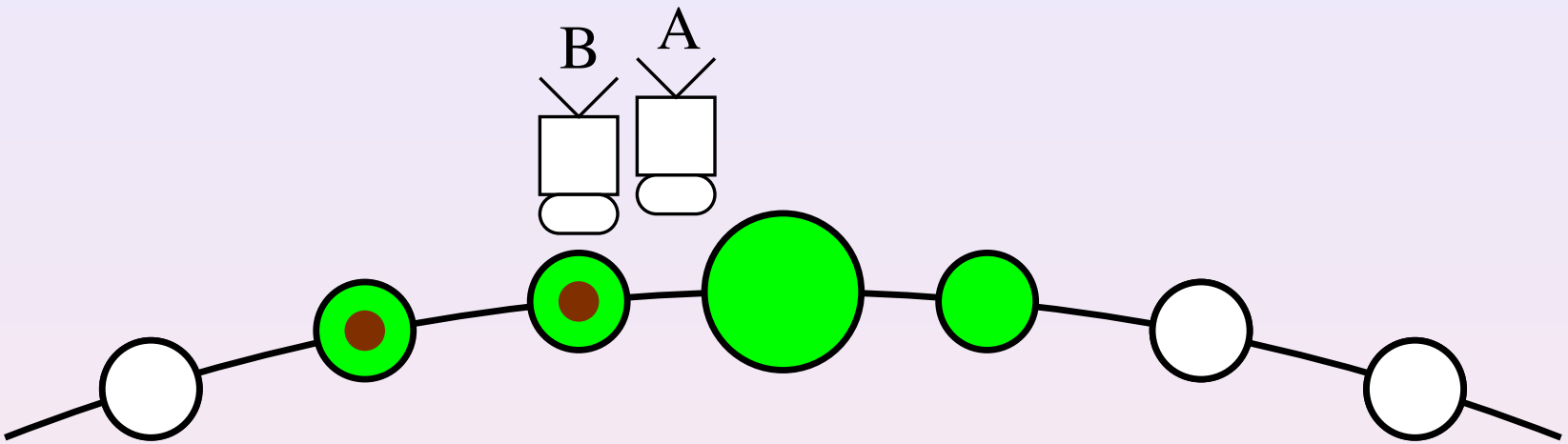

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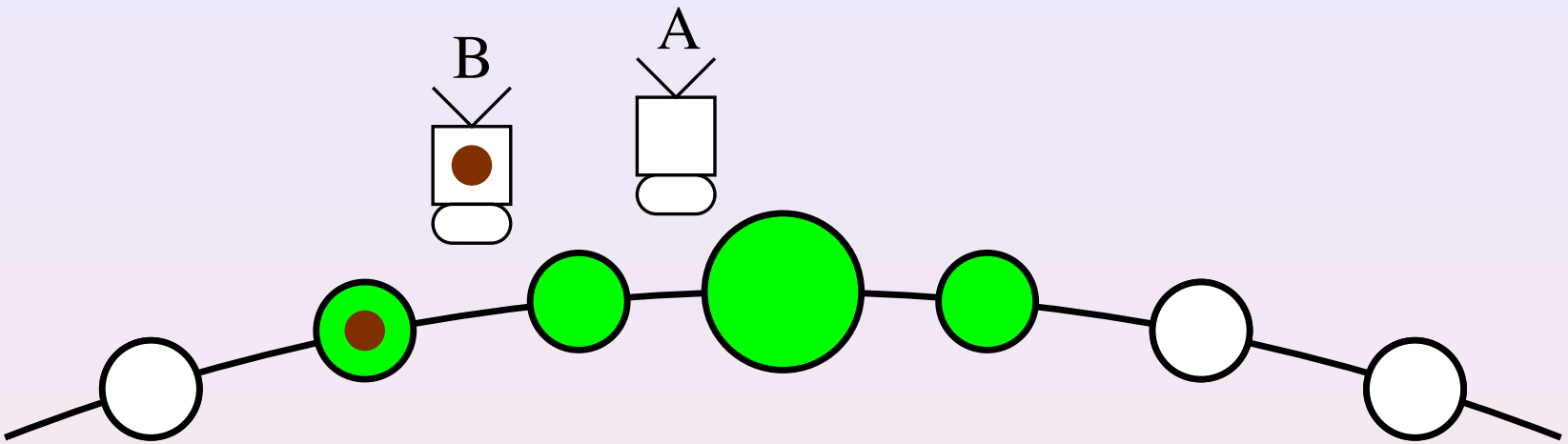

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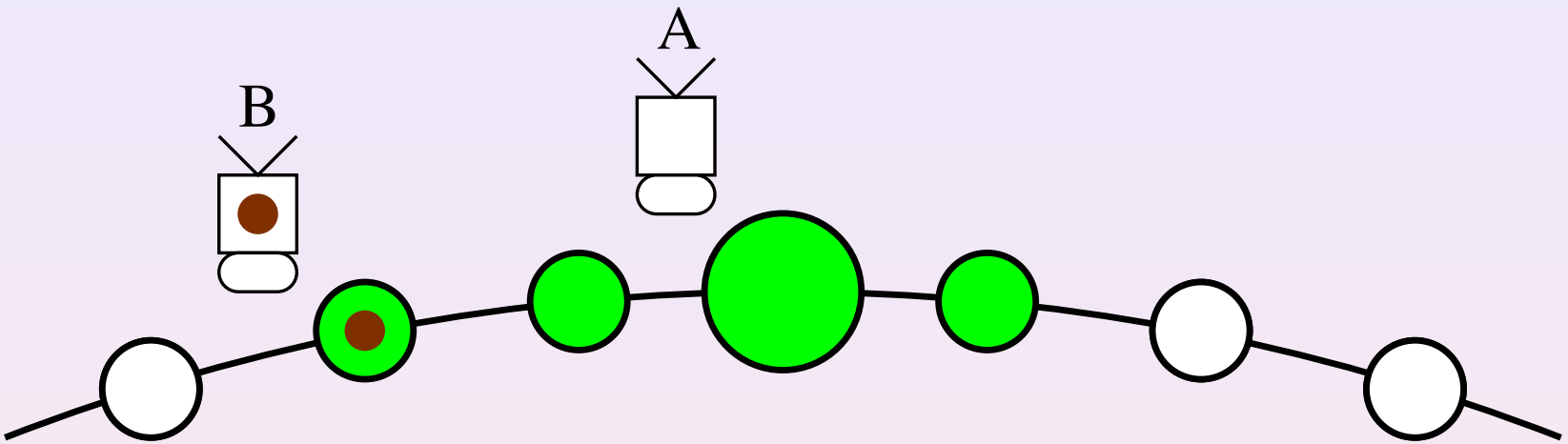

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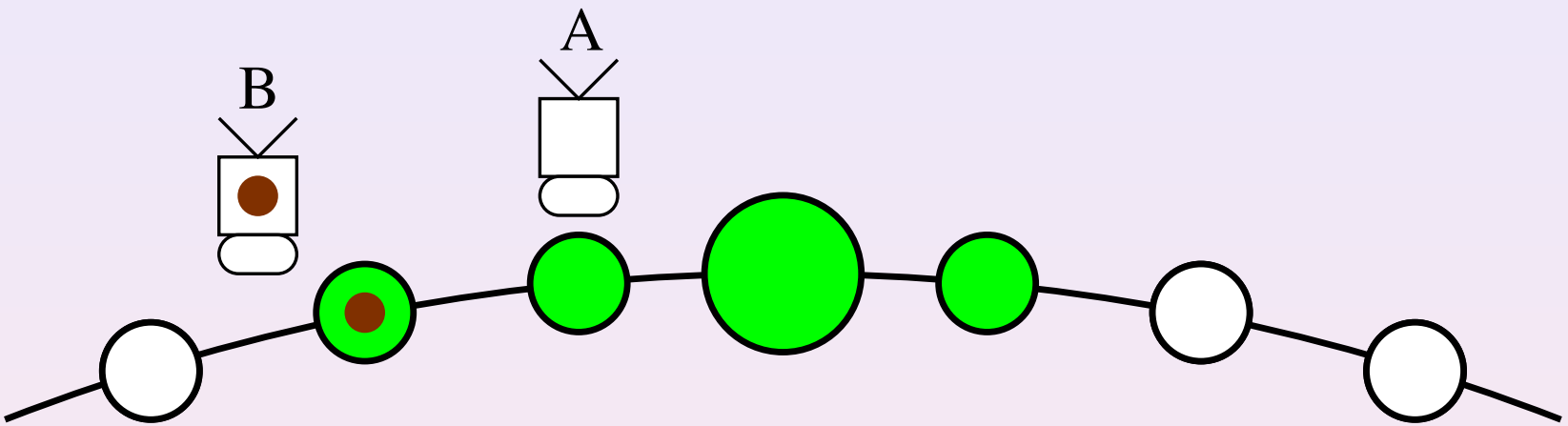

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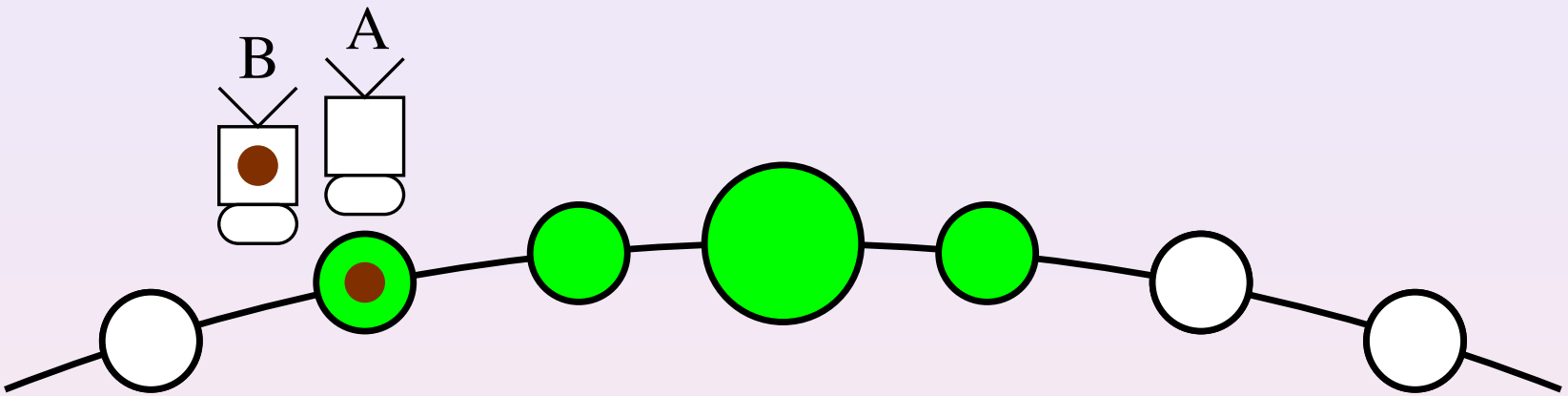

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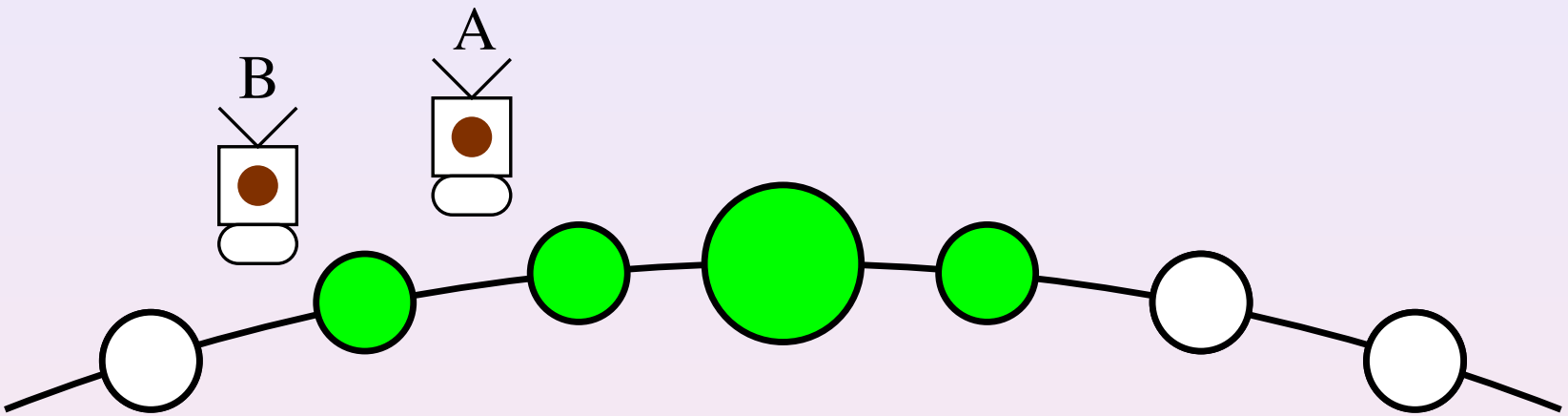

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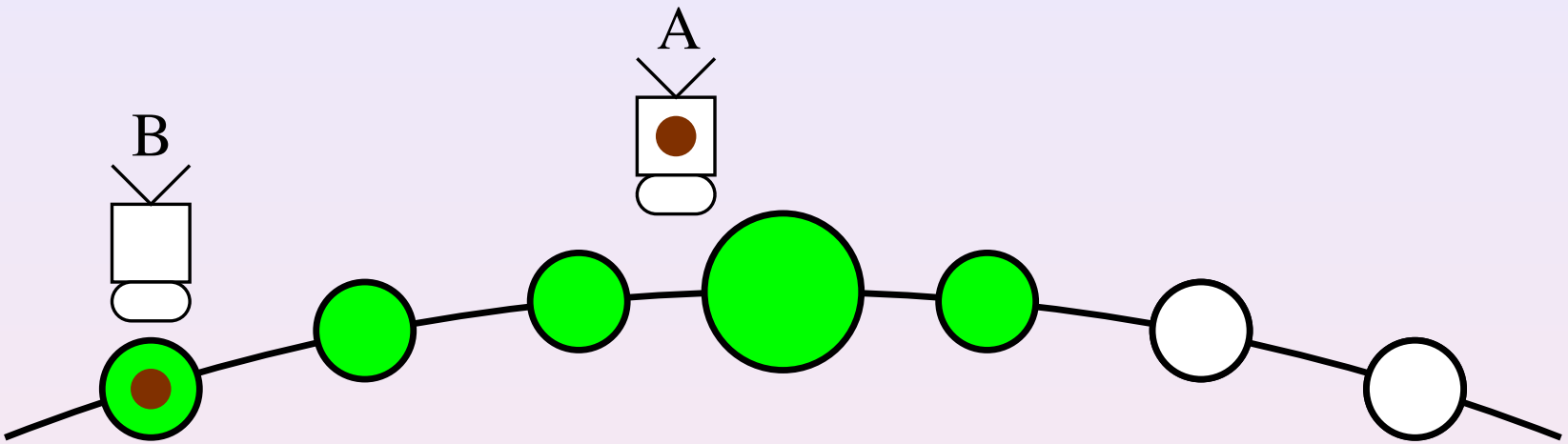

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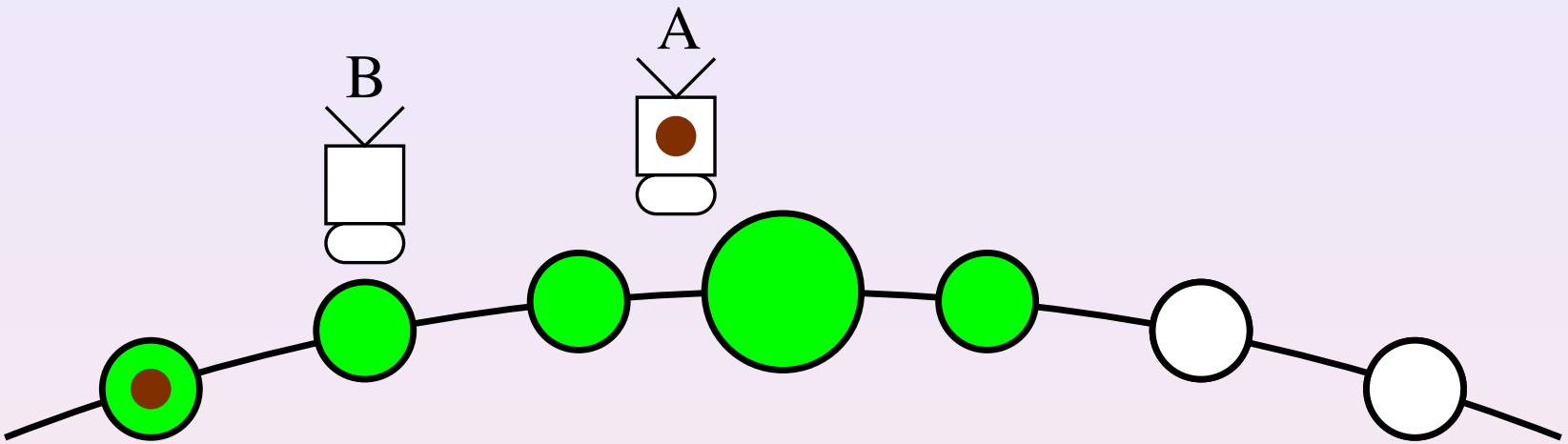

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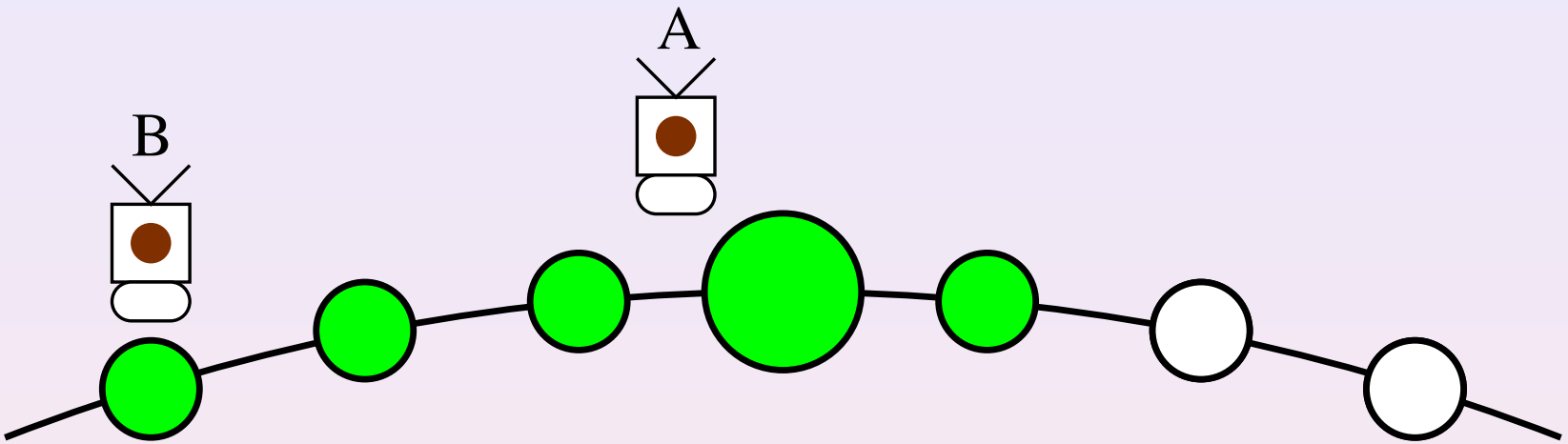

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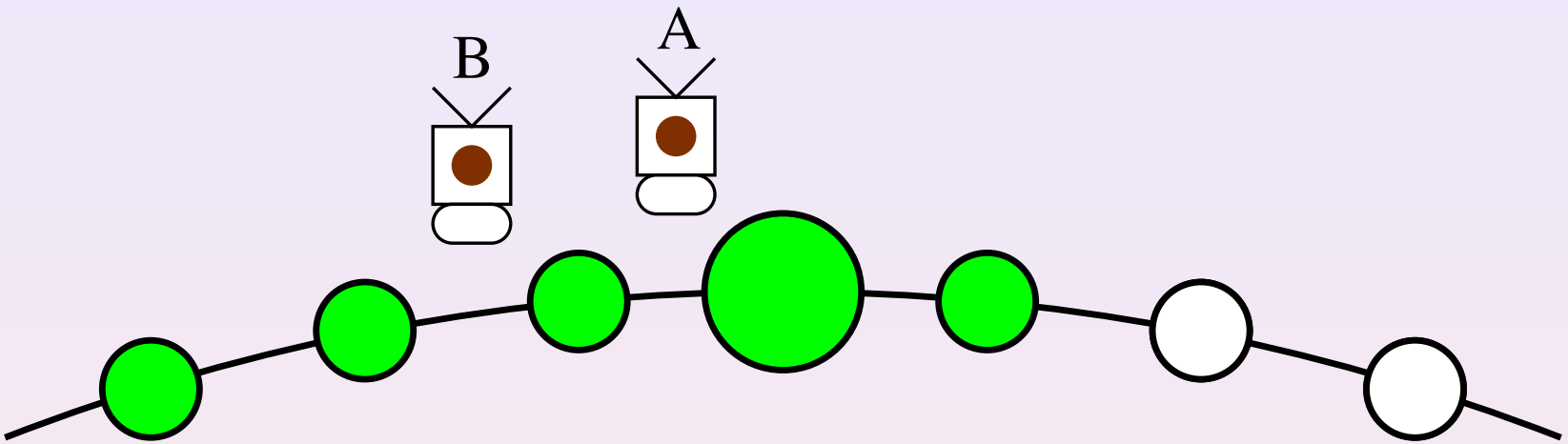

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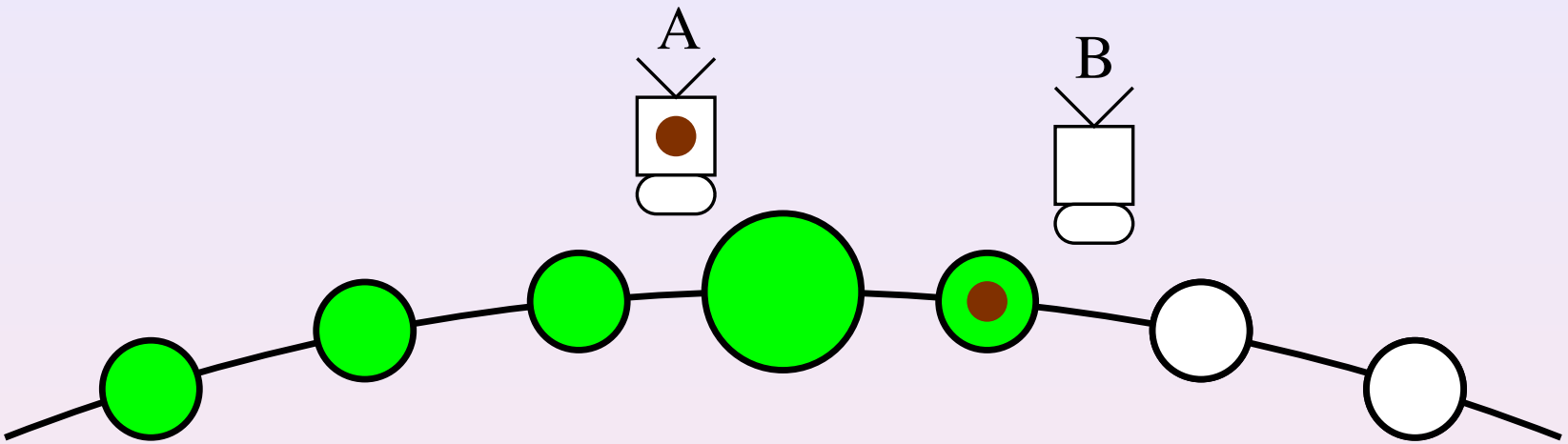

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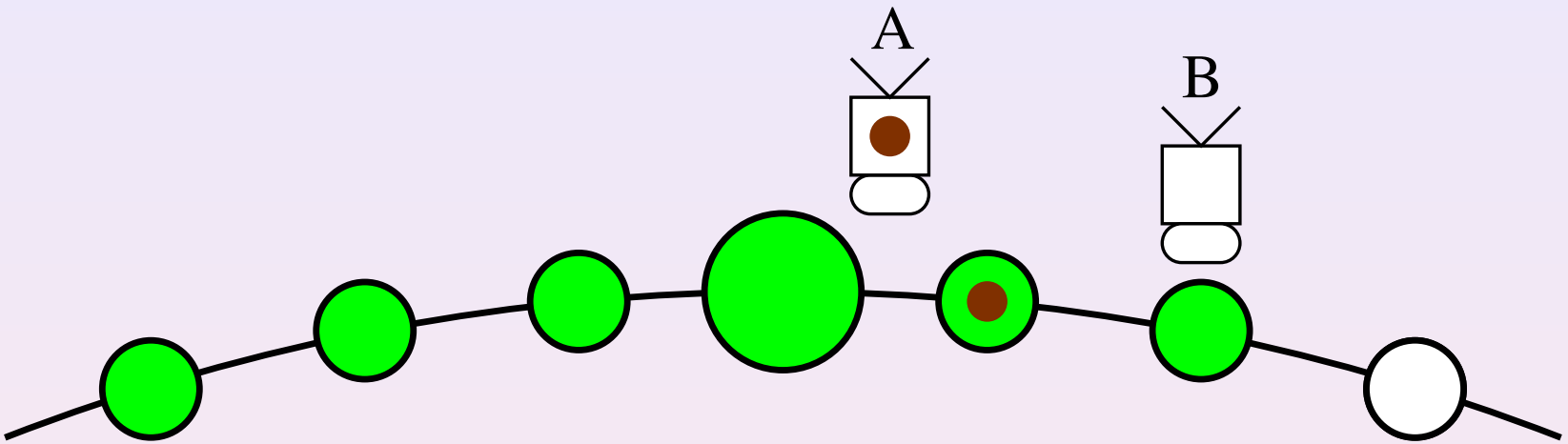

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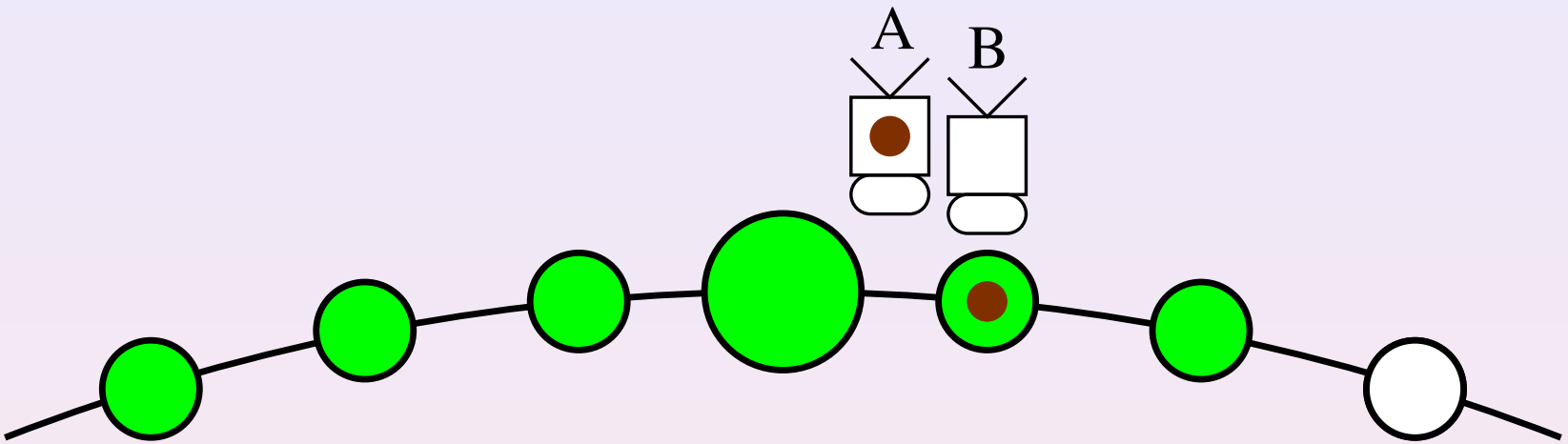

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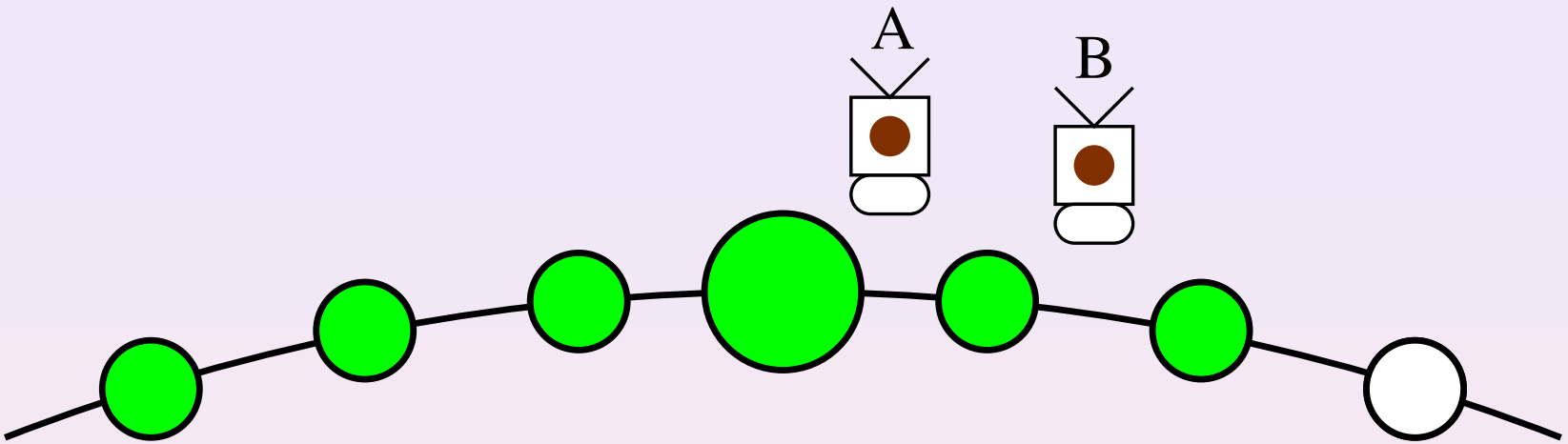

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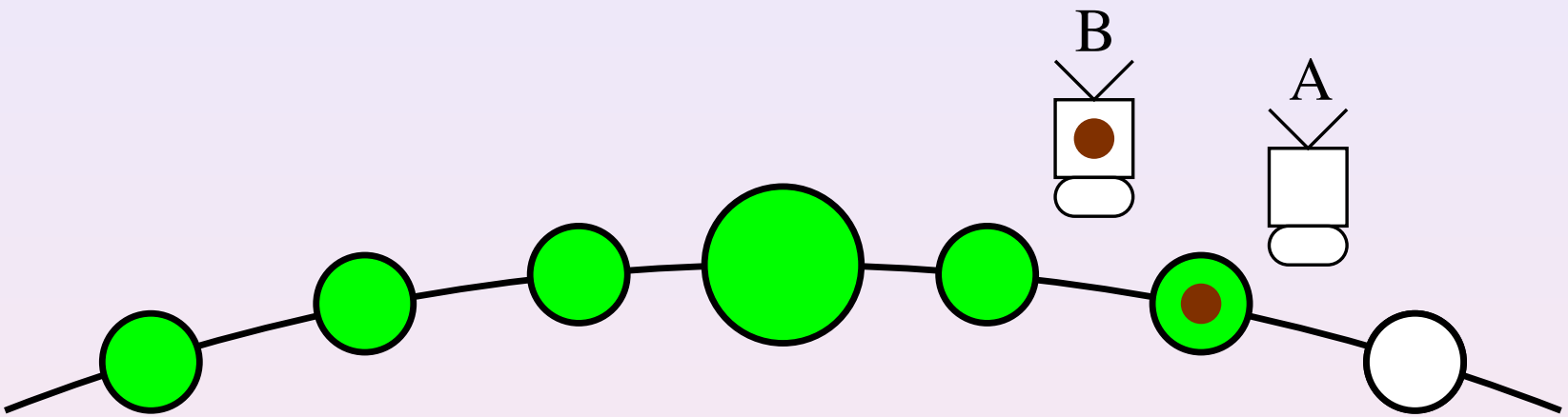

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Ping Pong algorithm

$\Rightarrow$ The algorithm is correct and uses $O(n^2)$ moves

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Enhanced Ping Pong algorithm

Quick description

- Execute Ping Pong **until** agents "meet" at least two/three nodes from the homebase (until the safe zone becomes sufficiently large)
- **While** still an unexplored node **do**
- Divide the unexplored part in two
- Each agent explores an half
- The first agent to finish its part goes and helps the other agent to explore the other part
- **When** an agent finds the pebble of the other agent
  - it moves the pebble by one node toward the center
  - and restart the loop

Analysis of Enhanced Ping Pong

Analysis

Between two halving

- Roughly half of the unexplored nodes are explored
- Agents do at most $O(n)$ moves

Result

- 1 pebble per agent
- 2 agents
- $\Theta(n \log n)$ moves

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Outline

Recent trends in distributed computing

Formalization / Generalization

- Simulation / equivalence between models
- Computational complexity theories for distributed computing

Towards more realistic scenarios

- More performance measures (incl. space complexity)
- Dynamic settings
- Distributed Computing inspired by nature
- Heterogeneous computing entities
- More complex tasks

The confidence issue in distributed computing

Quote from Lamport

[Concurrent (multiprocess)] algorithms can be quite subtle and hard to get right; their correctness proofs require a degree of precision and rigor unknown to most mathematicians (and many computer scientists).

Main reasons

- Multiple computing entities
- Non-determinism due to asynchrony and faults
- Importance of knowledge in impossibility results

Possible solutions

More structured and detailed proofs

Already advocated by Lamport in the 90's

Verification (model checking)

- Useful for finding bugs
- Restricted: combinatorial explosion or undecidability

Certification (proof assistants)

- Not fully automated anymore
- Huge expressiveness
- Can handle both algorithms and impossibility results

Distributed computing projects using Coq

Loco (not currently active)

- Formal framework for Local computations
- Developed at Bordeaux (LaBRI)

Verdi

- Framework for implementing and verifying dist. systems
- Developed in the University of Washington

Pactole

- Framework for robots on continuous and discrete spaces
- Developed in France (mainly Paris, Lyon, Grenoble)

PADEC

- A framework for certified self-stabilization
- Developed at Grenoble (Verimag)

Thank you to my co-authors

PhD students: Christian Glacet, Ahmed Wade, Antonin Lentz

Postdoc: Evangelos Bampas

My other co-authors (after my PhD):

H. Arfaoui, L. Blin, N. Bonichon, C. Cooper, J. Czyzowicz, S. Devismes, S. Dobrev, P. Flocchini, P. Fraigniaud, L. Gasieniec, C. Gavoille, N. Hanusse, J. Jansson, C. Johnen, R. Klasing, T. Kociumaka, A. Kosowski, D. Kowalski, A. Labourel, I. Lignos, R. Martin, F. Mathieu, N. Nisse, D. Pajak, A. Pelc, M. Potop-Butucaru, T. Radzik, K. Sadakane, N. Santoro, D. Soguet, W.-K. Sung, S. Tixeuil