Behavioral Simulations in MapReduce

JingYu Yang Jan 25th, 2011

Outline

Outline

- Motivation & Introduction
- Behavior Simulations In The State-Effect Pattern
- MapReduce For Simulations
- Programing Agent Behavior
- Experiments
- Conclusion

What is MapReduce?

- MapReduce is a framework for processing huge datasets on certain kinds of distributable problems using a large number of computers (nodes), collectively referred to as a cluster.
- "Map" step: The master node takes the input, chops it up into smaller sub-problems, and distributes those to worker nodes
- "Reduce" step: The master node takes the answers to all the sub-problems and combines them in some way to get the output

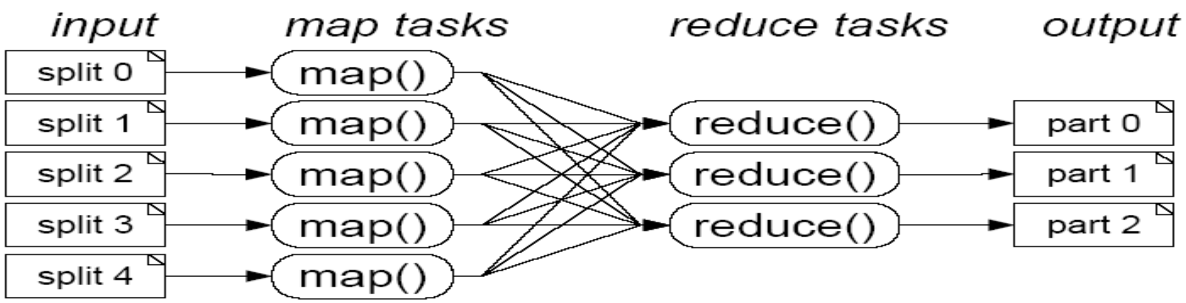
What is MapReduce?

- map : (k1;v1)->[(k2;v2)]

  produces a set of intermediate key-value pairs

- reduce : (k2; [v2])->[v3]

  collects all of the intermediate pairs with the same key and produces a value



Small Example

Word counting

map <word, “1”>

“document1”, “to be or not to be”

↓

“to”, “1”
“be”, “1”
“or”, “1”
…

Small Example

Reduce <key, sum>

key = "be" values = "1", "1"	key = "not" values = "1"	key = "or" values = "1"	key = "to" values = "1", "1"
↓	↓	↓	↓
"2"	"1"	"1"	"2"

"be", "2"
"not", "1"
"or", "1"
"to", "2"

What are Behavioral Simulations?

- Also called agent-based simulations
- Understand large complex systems
- Tackling the ecological and infrastructure challenges of our society.
- Application Areas
  Traffic,Ecology,Sociology,etc.

Why Behavioral Simulations?

- Traffic
  - –Congestion cost $87.2 billion in the U.S. in 2007
  - –Evaluating proposed traffic management systems before implementing them

- Ecology
  - –Use behavioral simulations to model collective animal motion, such as that of locust swarms or fish schools
  - –Crucial for they affect human food security

Challenges of Behavioral Simulations

- Easy to program →not scalable

- Scalable →hard to program

- Purpose: close the gap

Requirements for Simulation Platforms

- Support for Complex Agent Interaction
- Automatic Scalability
- High Performance
- Commodity Hardware
- Simple Programming Model

Contribution

- show how behavioral simulations can be abstracted in the state-effect pattern
- show how MapReduce can be used to scale behavioral simulations
- present a new scripting language for simulations
- perform an experimental evaluation with two real-world behavioral simulations

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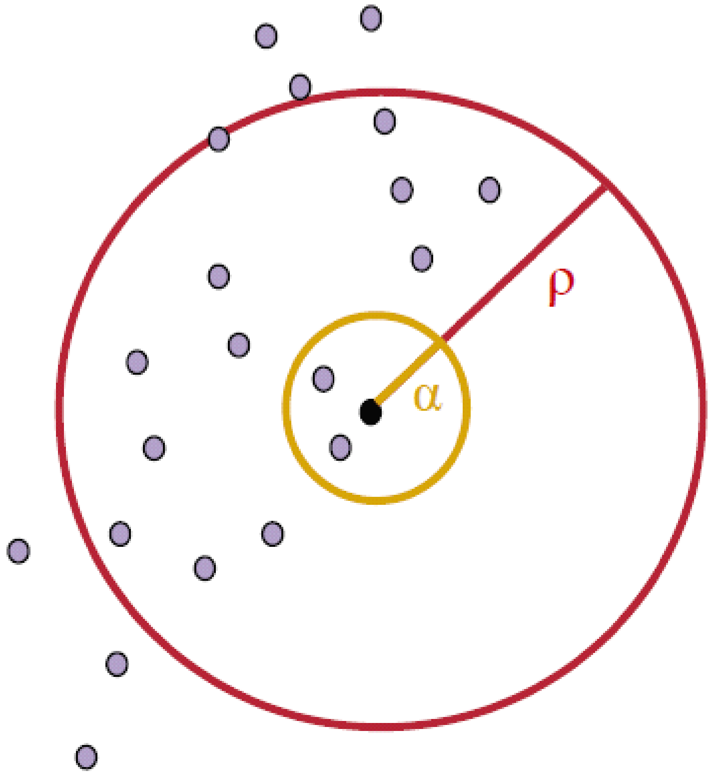
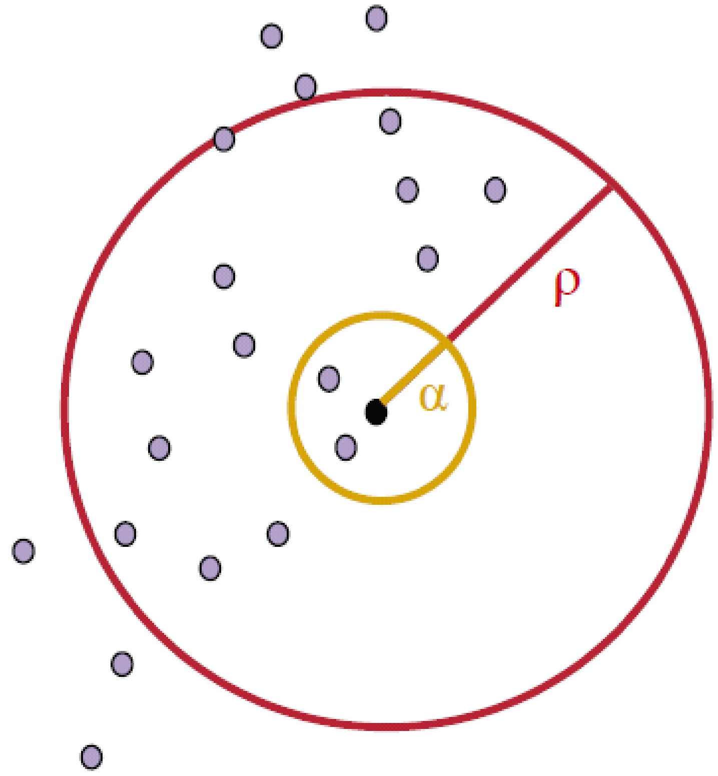
A Running Example: Fish Schools

- Fish Behavior
- –Avoidance: if too close, repel other fish
- –Attraction: if seen within range, attract other fish



A Running Example: Fish Schools

- Time-stepping: agents proceed in ticks
- Concurrency: agents are concurrent within a tick
- Interactions: agents continuously interact
- Spatial Locality: agents have limited visibility



Traditional Solutions for Concurrency

- Preempt conflicts
- Avoiding conflicts (Rollback in case of conflicts)

- Problems:
  - –Frequency of local interactions among agents →many conflicts
  - –Poor scalability

    due to either excessive synchronization or frequent rollbacks

State-Effect Pattern

- Programming pattern to deal with concurrency
- Time-stepped model

  ticks→represent the smallest time period of interest
- Events occur during same tick can be reordered or parallelized
- Basic Idea:separate read and write operation

  limit the synchronization necessary between agents

State-Effect Pattern

- States:

  –public attributes that are updated only at tick boundaries

  state attributes remain fixed during a tick

  Only need to be synchronized at the end of each tick

- Effects:

  –intermediate computations as agents interact to calculate new states

  effect attribute has an associated decomposable and order-independent combinator function for combining multiple assignments

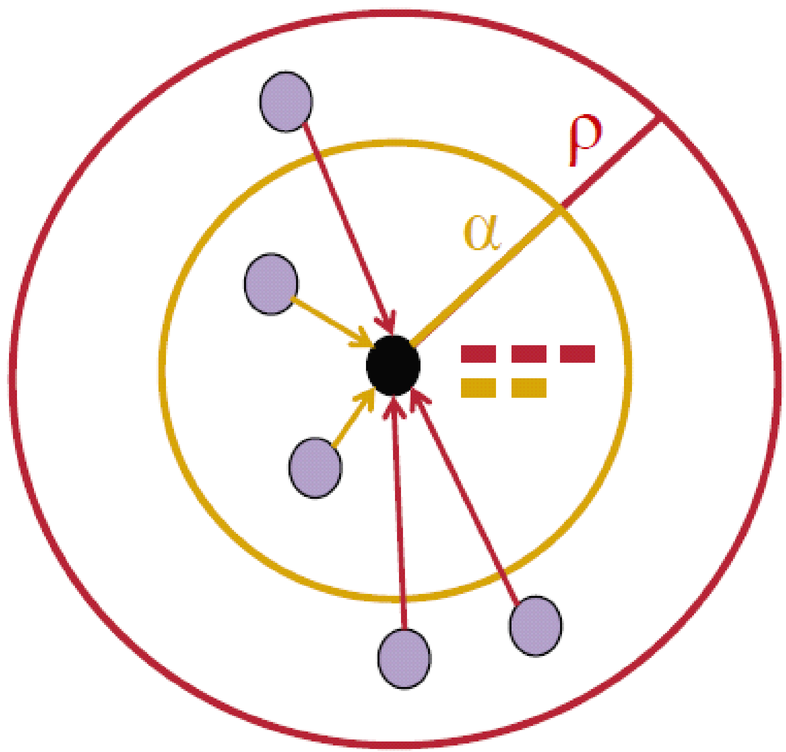
States and Effects

- States:
  –Snapshot of agents at the beginning of the tick

  position, velocity vector

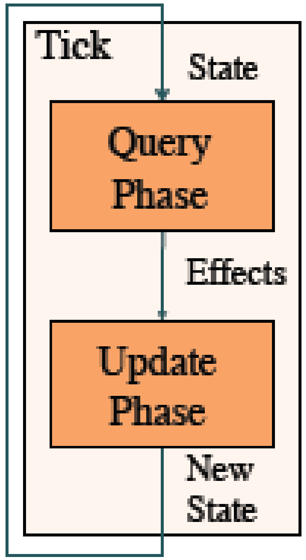
- Effects:
  –Intermediate results from interaction, used to calculate new states

  sets of forces from other fish



Two Phases of a Tick

- Query Phase: agents inspect their environment to compute effects
  - –Read states →write effects
  - –Effect values combined using the appropriate combinator function
  - –Effect writes are order-independent
- Update Phase: agents update their own state
  - –Read effects →write states
  - –Reads and writes are totally local
  - –State writes are order-independent



Two Phases of a Tick

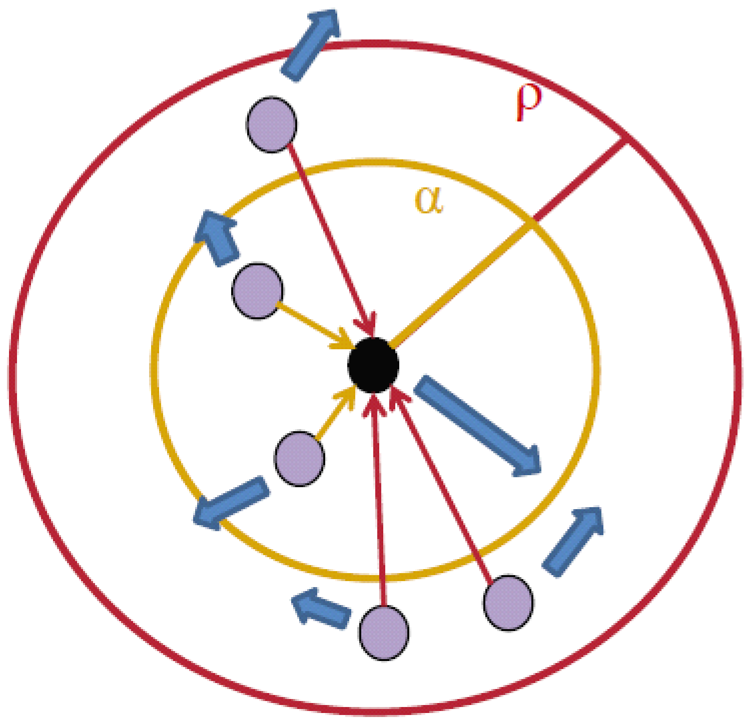
- Only way that agents can communicate is through effect assignments in the query phase
- local assignment

  agent updates one of its own effect attributes
- non-local assignment

  agent writes to an effect attribute of a different agent

A Tick in Fish Simulation

- Query
  - –For fish f in visibility α:
  - •Write repulsion to f's effects
  - –For fish f in visibility ρ:
  - •Write attraction to f's effects
- Update
  - –new velocity = combined repulsion + combined attraction + old velocity
  - –new position = old position + old velocity



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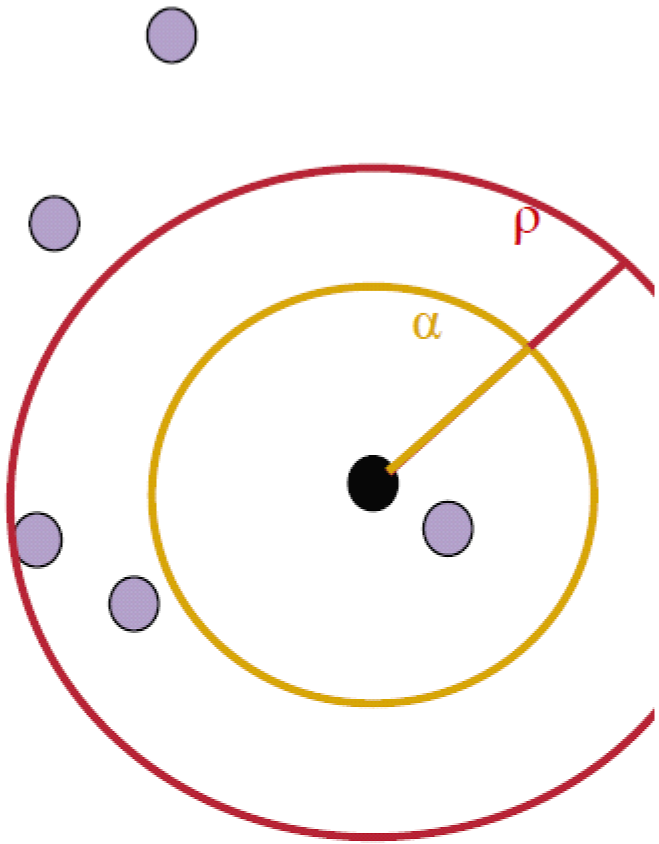

The Neighborhood Property

- Synchronization at tick boundaries may still be very expensive
- Don't needs to query every other agent in the simulated world to compute its effects
- Most behavioral simulations are spatial, and simulated agents can only interact with other agents that are close according to a distance metric

The Neighborhood Property

- visibility

  visible region

  the region of space containing agents

  that this agent can read from or assign effects to

- reachability

  reachable region

  the region that the agent can move to after the update phase.

（reachable region will be a subset of its visible region ，is not required）

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Simulations as Iterated Spatial Joins

- Since agents only query other agents within their visible regions, processing a tick is similar to a spatial selfjoin

- Join each agent with the set of agents in its visible region and perform the query phase using only these agents

- Update phase:agents move to new positions within their reachable regions and we perform a new iteration of the join during the next tick

Iterated Spatial Joins in MapReduce

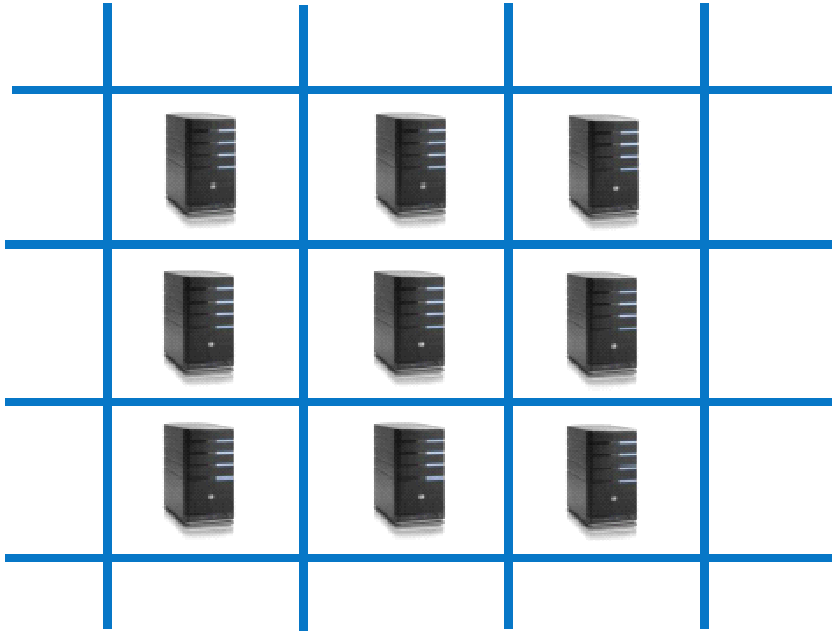
- Map task
  spatially partitioning agents into a number of disjoint regions
- Reduce task

  join the agents using their visible regions

effects	map_1^t	$reduce_1^t$	map_2^t	$reduce_2^t$	map_1^{t+1}
local	$update^{t-1}$ $distribute^t$	$query^t$	—	—	$update^t$ $distribute^{t+1}$
non-local	$update^{t-1}$ $distribute^t$	non-local $effect^t$	—	effect $aggregation^t$	$update^t$ $distribute^{t+1}$

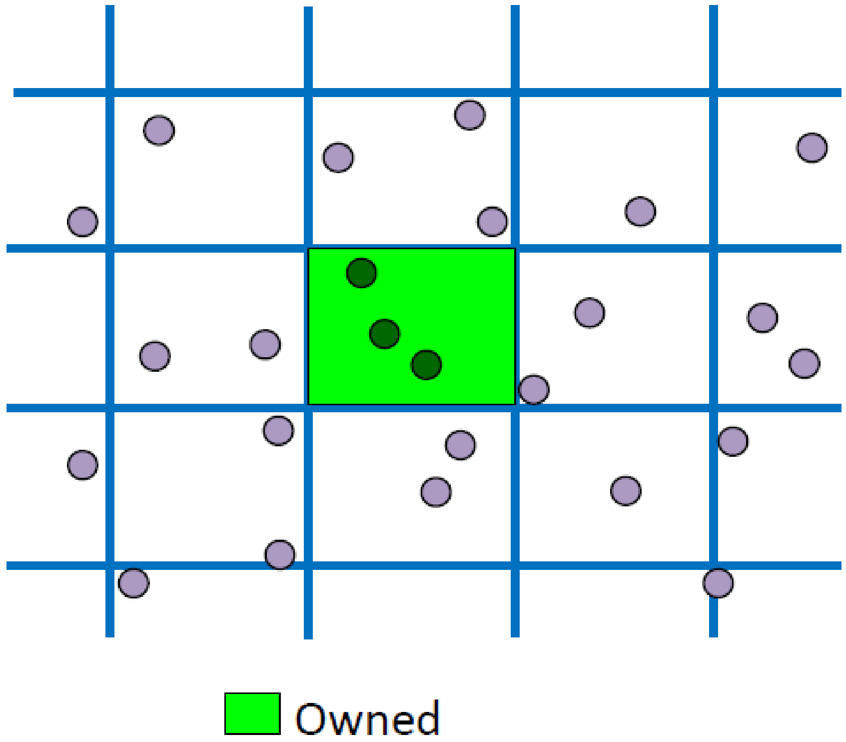
Table 1: The state-effect pattern in MapReduce

- Partition simulation space into regions, each handled by a separate node



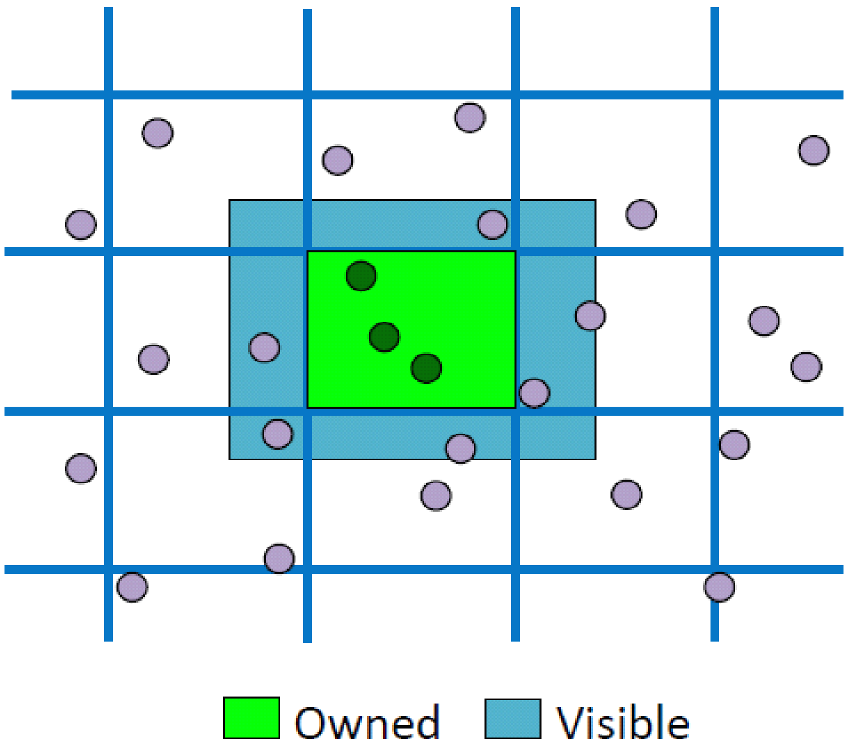
Communication Between Partitions

- Owned Region: agents in it are owned by the node



Communication Between Partitions

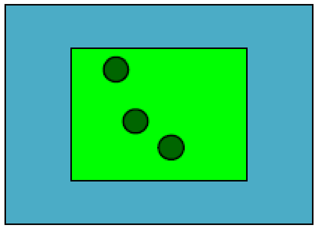
- Visible Region: agents in it are not owned, but need to be seen by the node
- The map task replicates each agent a to every partition that contains a in its visible region.

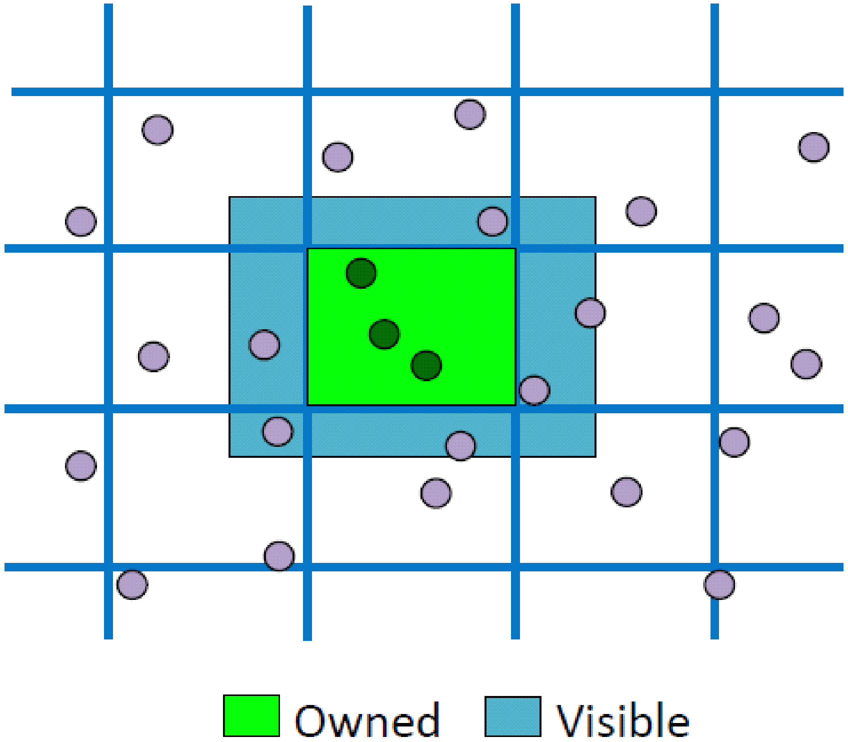


Communication Between Partitions

- Visible Region: agents in it are not owned, but need to be seen by the node

State Communication





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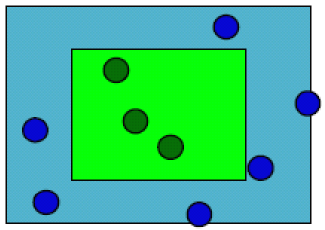
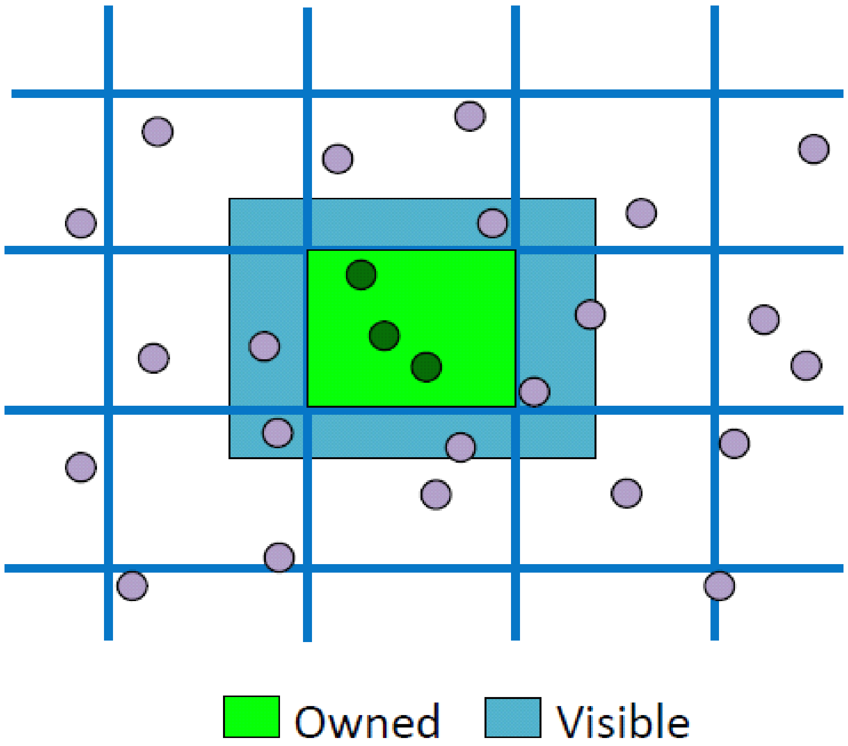
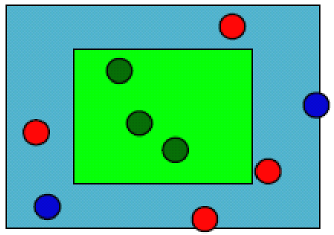


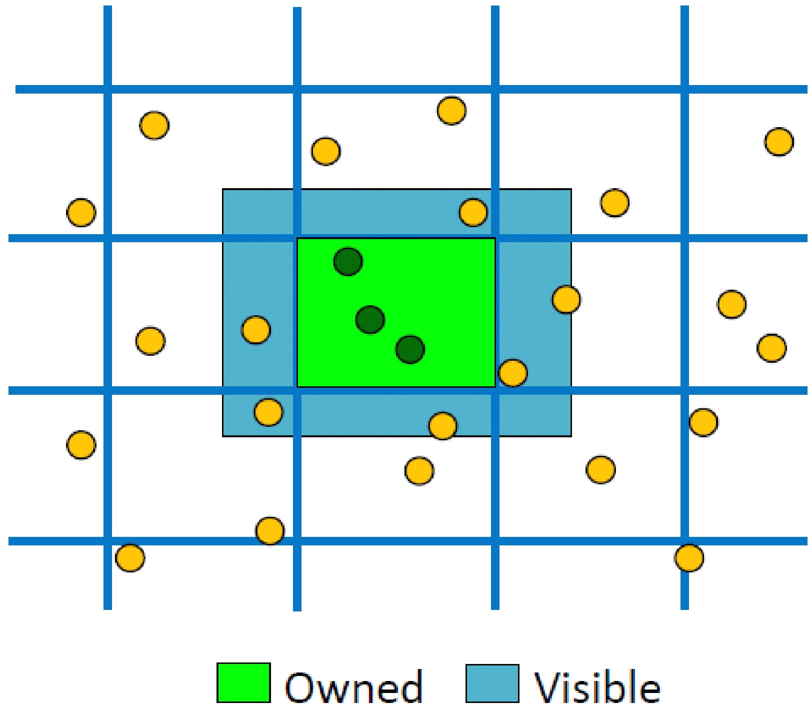


Communication Between Partitions

- Visible Region: agents in it are not owned, but need to be seen by the node

Query

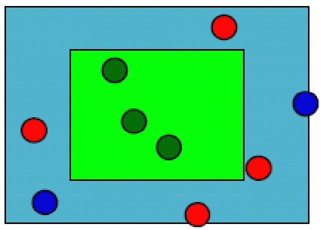


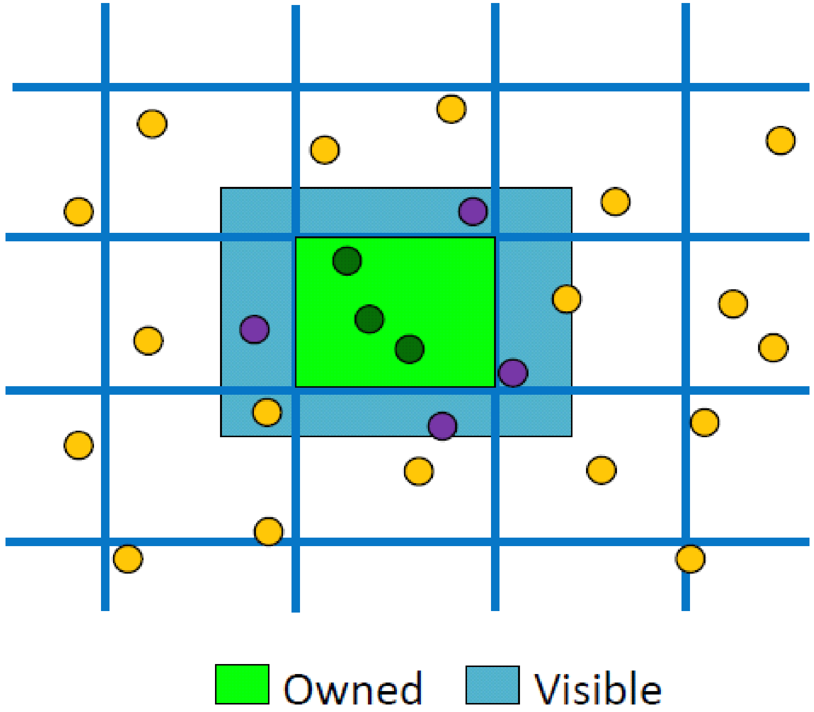


Communication Between Partitions

- Visible Region: agents in it are not owned, but need to be seen by the node

Effect communication

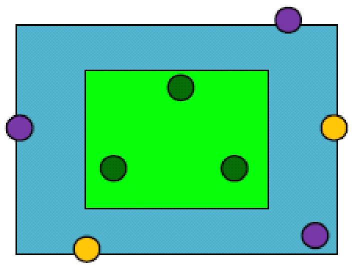


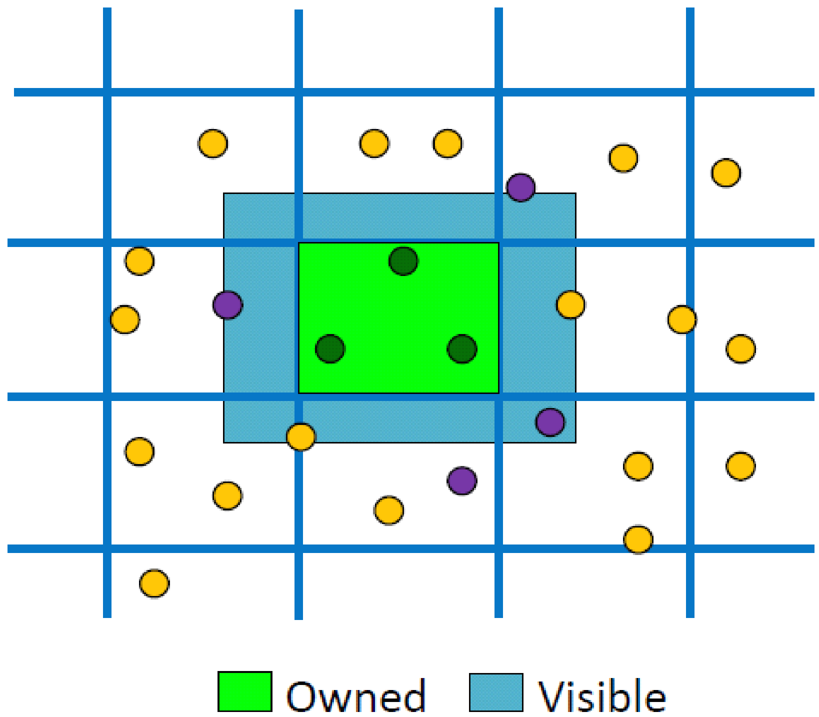


Communication Between Partitions

- Visible Region: agents in it are not owned, but need to be seen by the node

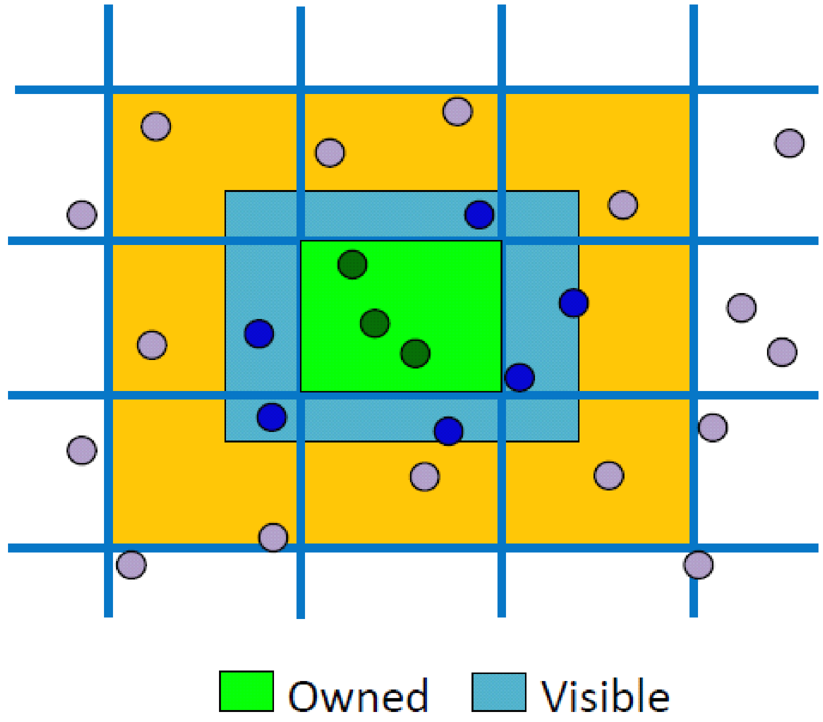
Update





Communication Between Partitions

- Visible Region: agents in it are not owned, but need to be seen by the node
- Only need to com-municate with neighbors to
  - –refresh states
  - –forward assigned effects



Local Effects Assignment

•Map^t_1:tick t begins when the first map task, assigns each agent to a partition ($distribute^t$).

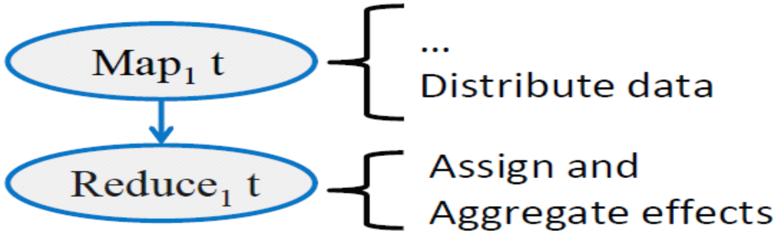
• $Reduce^t_1$:outputs a copy of each agent it owns after executing the query phase and updating the agent's effects.

•The tick ends when the next map task, map^{t+1}_1 , executes the update phase ($update^t$).

effects	map^t_1	$reduce^t_1$	map^t_2	$reduce^t_2$	map^{t+1}_1
local	$update^{t-1}$ $distribute^t$	$query^t$	—	—	$update^t$ $distribute^{t+1}$
non-local	$update^{t-1}$ $distribute^t$	non-local $effect^t$	—	effect $aggregation^t$	$update^t$ $distribute^{t+1}$

Table 1: The state-effect pattern in MapReduce

Local Effects Assignment



Do not have non-local effects

effects	map_1^t	reduce_1^t	map_2^t	reduce_2^t	map_1^{t+1}
local	update^{t-1} distribute^t	query^t	—	—	update^t distribute^{t+1}
non-local	update^{t-1} distribute^t	non-local effect^t	—	effect aggregation^t	update^t distribute^{t+1}

Table 1: The state-effect pattern in MapReduce

Non-Local Effects Assignment

- Using two MapReduce passes
- The first map task, map^t_1, is the same
- The first reduce task, $reduce^t_1$, performs non-local effect assignments to its replicas (non-local $effect^t$)
- Second map task:only necessary for distribution,not perform any computation
- $reduce^t_2$： computes the final value for each aggregate (effect $aggregation^t$)
- Also called map-reduce-reduce model

effects	map^t_1	$reduce^t_1$	map^t_2	$reduce^t_2$	map^{t+1}_1
local	$update^{t-1}$ $distribute^t$	$query^t$	—	—	$update^t$ $distribute^{t+1}$
non-local	$update^{t-1}$ $distribute^t$	non-local $effect^t$	—	effect $aggregation^t$	$update^t$ $distribute^{t+1}$

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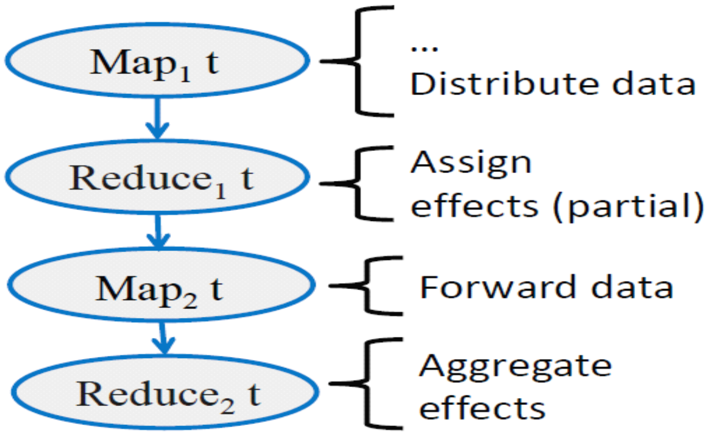
Non-Local Effects Assignment



effects	map_1^t	$reduce_1^t$	map_2^t	$reduce_2^t$	map_1^{t+1}
local	$update^{t-1}$ $distribute^t$	$query^t$	—	—	$update^t$ $distribute^{t+1}$
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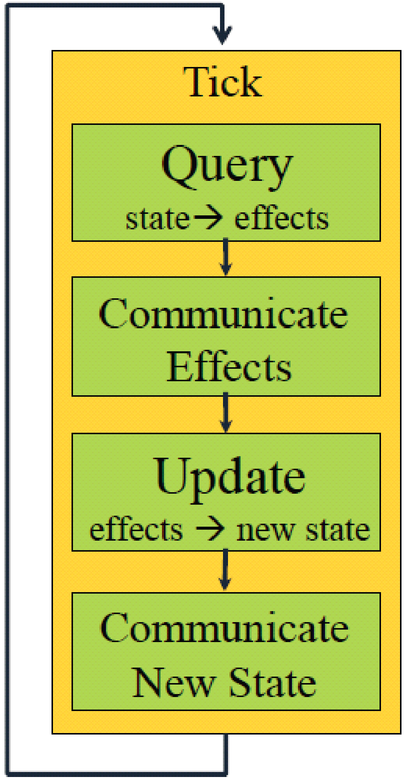
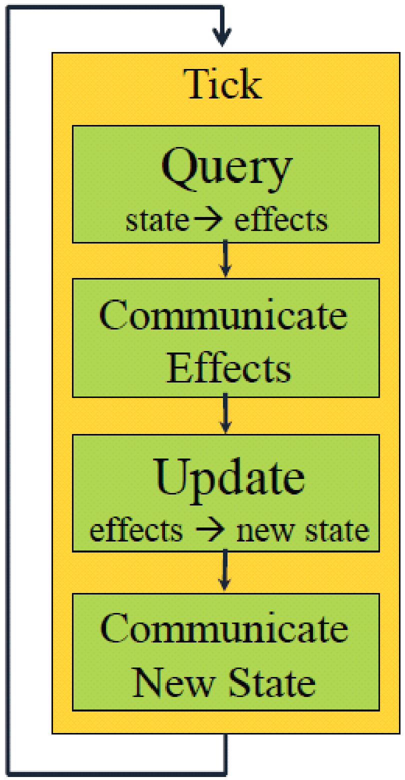
From State-Effect to Map-Reduce



From State-Effect to Map-Reduce

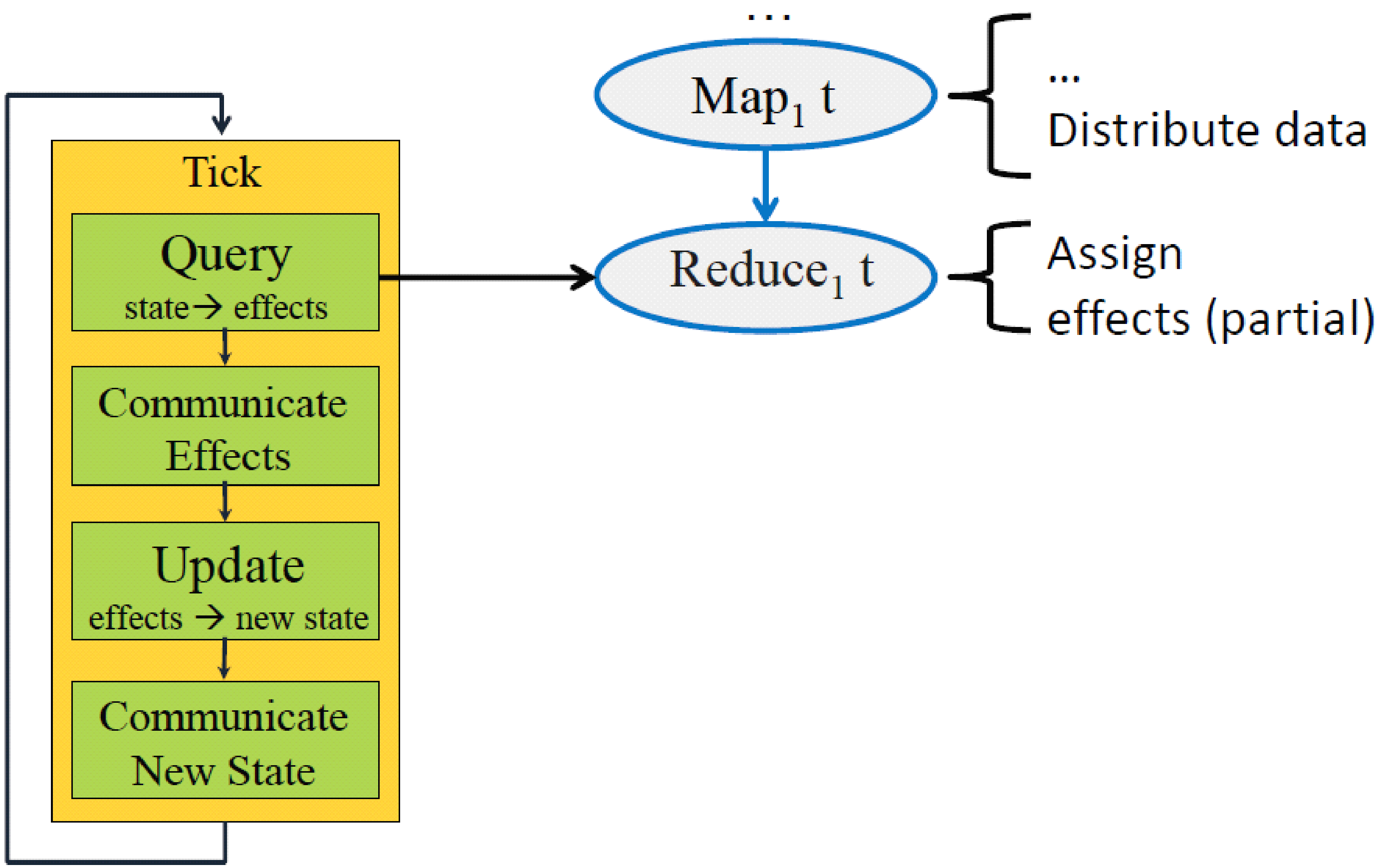


Map_1 t

...

Distribute data

From State-Effect to Map-Reduce



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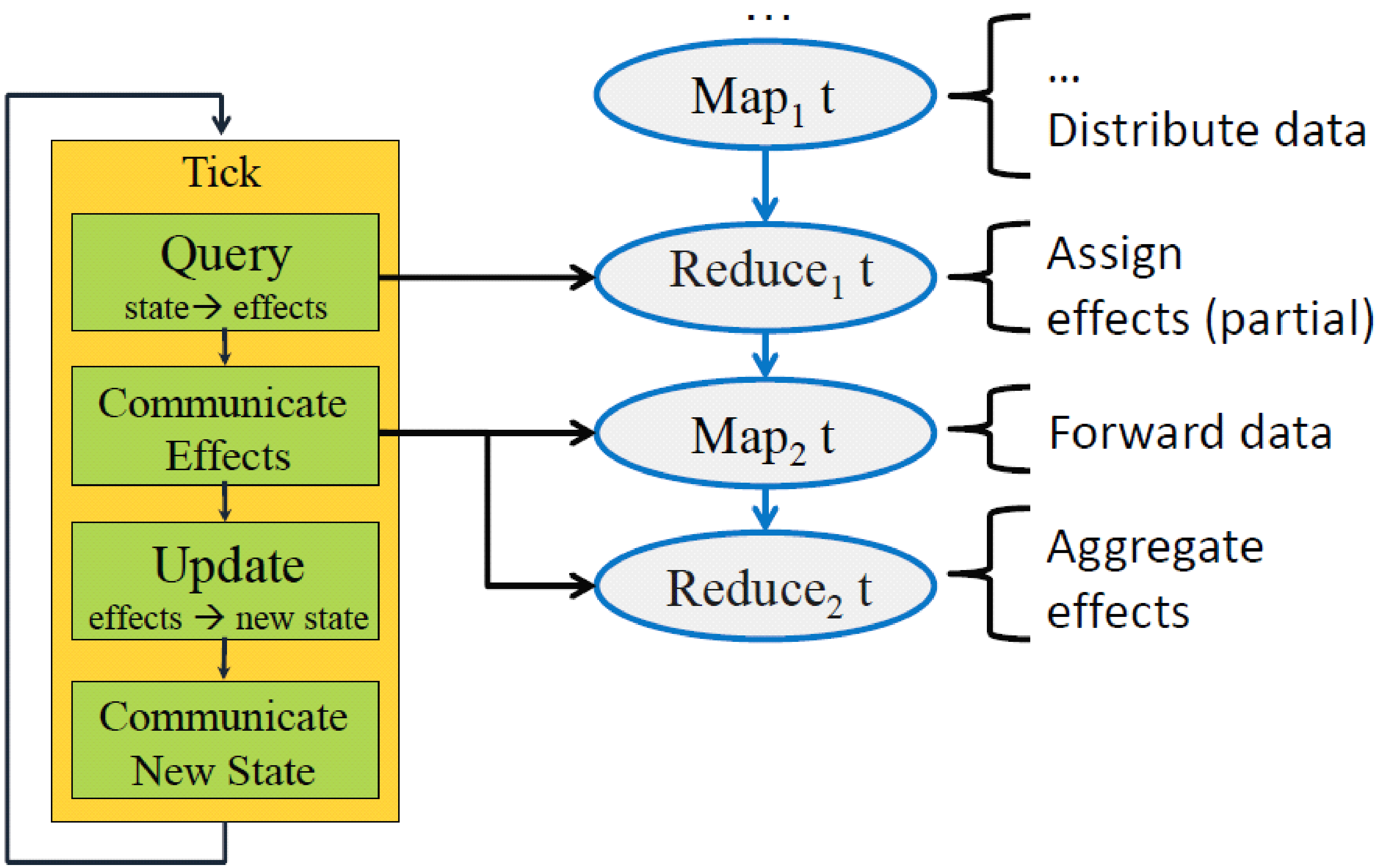
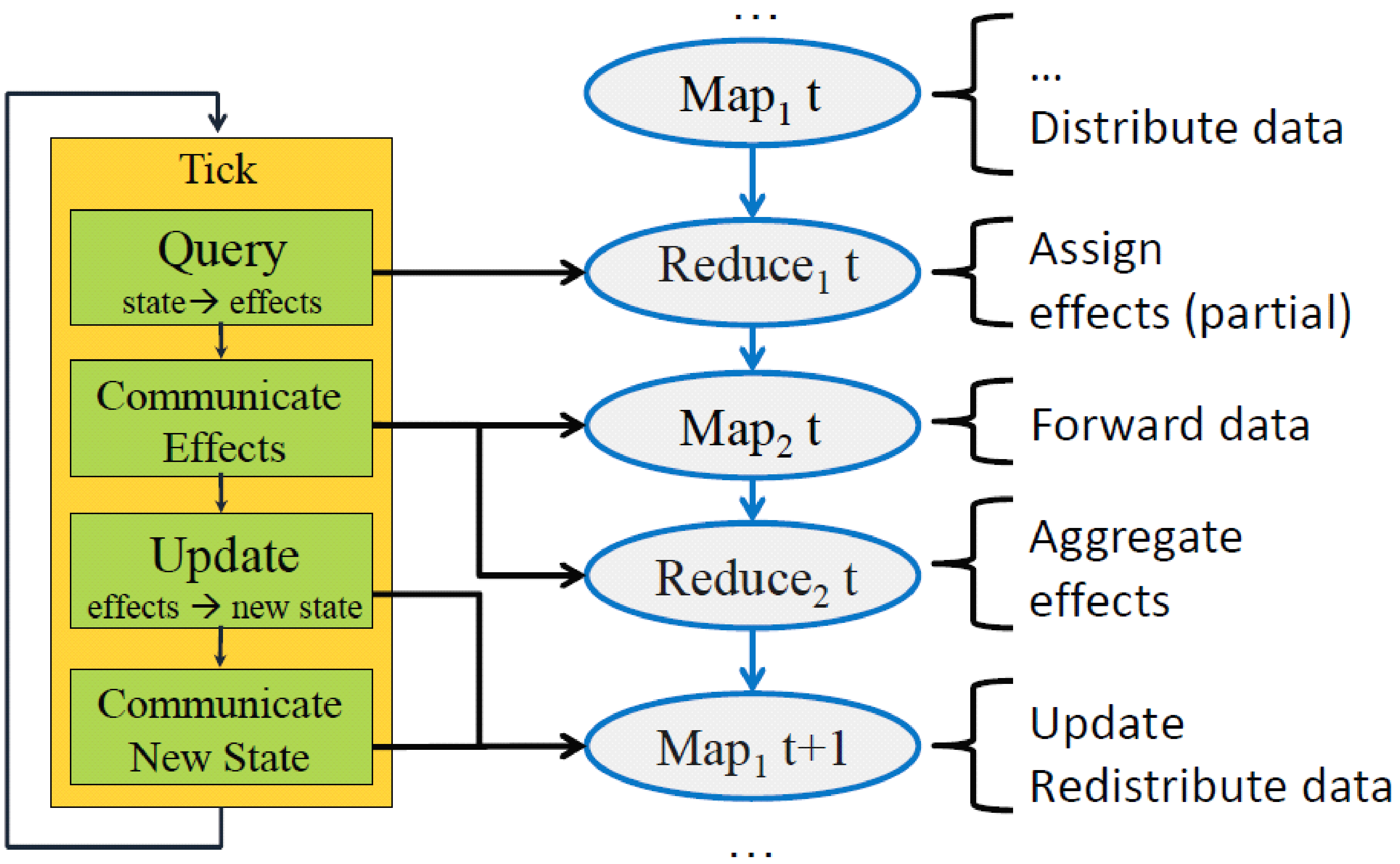


From State-Effect to Map-Reduce



BRACE(Big Red Agent Computation Engine)

- Special-purpose MapReduce engine for behavioral simulations
- Goal of BRACE：process a very large number of ticks efficiently, and to avoid I/O or communication overhead
- Why introducing Brace?

  behavioral simulations have considerably different characteristics than traditional MapReduce applications

BRACE(Big Red Agent Computation Engine)

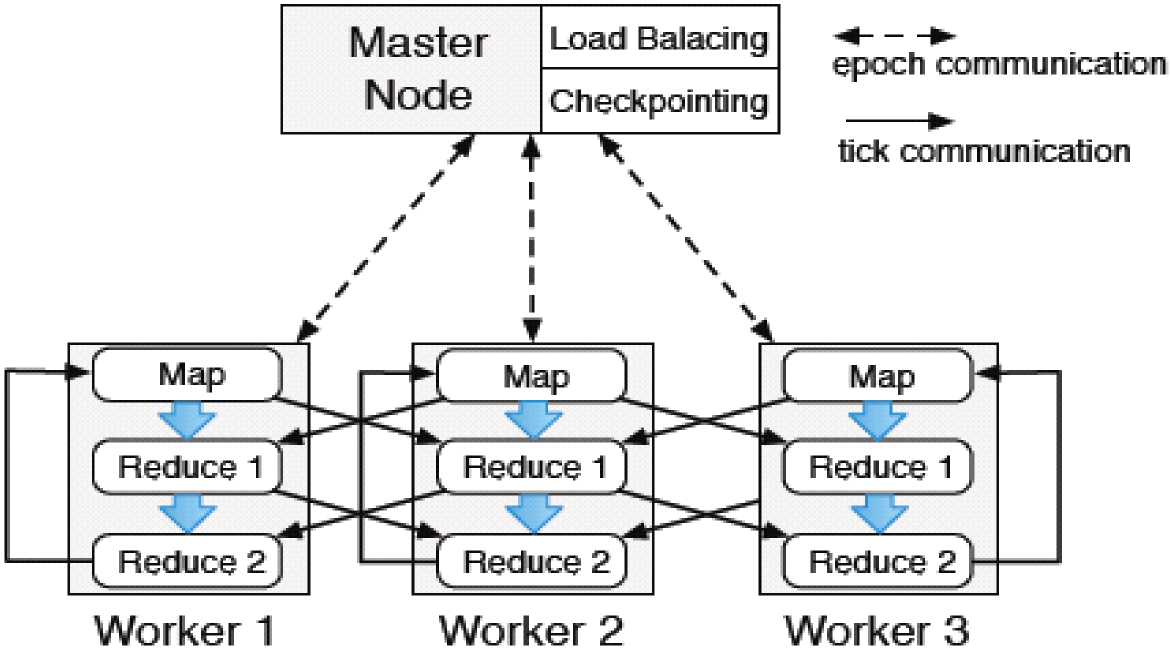


Figure 1: BRACE Architecture Overview

BRACE(Big Red Agent Computation Engine)

- Shared-Nothing, Main-Memory Architecture

  expect data volumes to be modest, so BRACE executes map and reduce tasks entirely in main memory

- Fault Tolerance

  employ epoch synchronization with the master to trigger coordinated checkpoints

- Partitioning and Load Balancing

- Collocation of Tasks

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BRASIL(Big Red Agent SImulationLanguage)

- High-level language for domain scientists
  closer to the scientific models that describe agent behavior
- object-oriented language
- Programs specify behavior logic of individual agents

BRASIL(Big Red Agent SImulationLanguage)

- looks superficially like Java
  The programmer can specify fields, methods, and constructors
- each field in class must be tagged as either state or effect
- query phase expressed by run() method
- State fields are read-only
- Effect assignments are aggregated at the effect field
- Has some important restrictions

Fish in BRASIL

```
class Fish {
  // The fish location & vel (x)
  public state float x : (x+vx); #range[-1,1];
  public state float vx : vx + rand() + avoidx / count * vx;
  // Used to update our velocity (x)
  private effect float avoidx : sum;
  private effect int count : sum;
  ...
```

Update rule

Visibility

Effect combinator

```
class Fish {
  // The fish location & vel (x)
  ...

  /** The query-phase for this fish. */
  public void run() {
    // Use "forces" to repel fish too close
    foreach(Fish p : Extent<Fish>) {
      p.avoidx <- 1 / abs(x - p.x);
      ...
      p.count  <- 1;
    }
  }
}
```

Effect assignment

Effect Inversion

- An important optimization that is unique to our framework involves eliminating non-local effects.
- Rewritten expression does not change the results of the simulation,but only assigns effects locally.

```
foreach(Fish p : Extent<Fish>) {
     avoidx <- 1 / abs(p.x - x);
     avoidy <- 1 / abs(p.y - y);
     count <- 1;
}
```

Effect Inversion

- Theorem: Every behavioral simulation written in BRASIL that uses non-local effects can be rewritten to an equivalent simulation that uses local effects only

  –Proof in the VLDB 2010 paper

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Experimental Setup

- Implementation
  - –BRACE MapReduce runtime implemented in C++ ,Our BRASIL compiler, written in Java and directly generates C++
  - –Grid partitioning

    assigns each grid cell to a separate slave node
  - –Include KD-Tree spatial indexing, rebuild every tick
  - –Basic load balancing
  - –Checkpointing is not yet integrated
- Simulation Workloads

  implemented realistic traffic and fish school simulations
- Hardware: Cornell WebLabCluster (60 nodes, 2xQuadCore Xeon 2.66GHz, 4MB cache, 16GB RAM)

Traffic: Indexing vs. Seg. Length

- Compares the performance of MITSIM against BRACE using BRASIL

- Without spatial indexing:

  Brace's Performance Degrades quadratically with increasing segment length

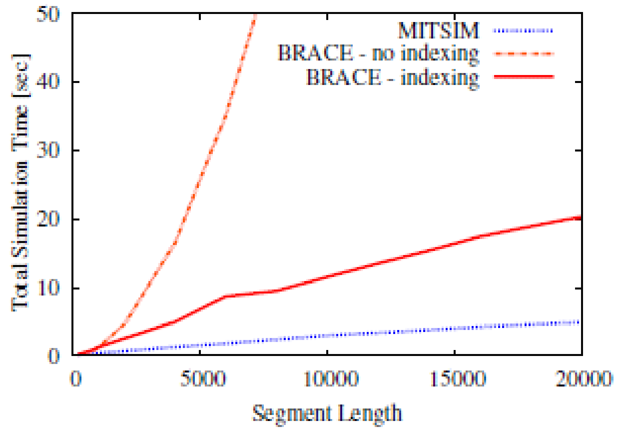

Figure 3: Traffic: Indexing vs. Seg. Length

Fish: Indexing vs. Visibility

- increase the visibility range:

  KD-tree indexing performance decreases

- indexing yields from two to three times improvement over a range of visibility values.

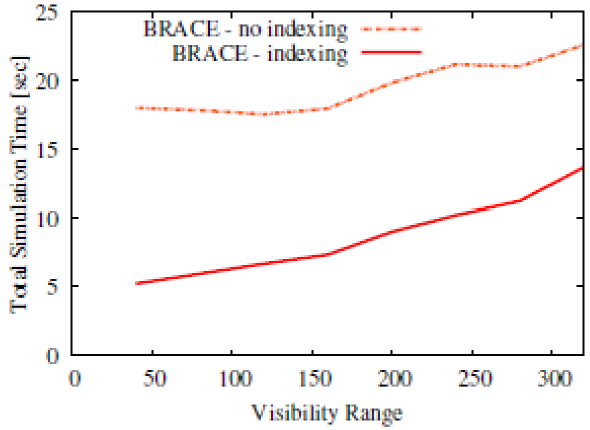

Figure 4: Fish: Indexing vs. Visibility

Predator: Effect Inversion

- Effect Inversion increases agent tick throughput
  – from 3.59 million (Idx-Only) to 4.36 million (Idx+Inv) with KD-tree indexing enabled
  – from 2.95 million (No-Opt) to 3.63 million (Inv-Only) with KD-tree indexing disabled

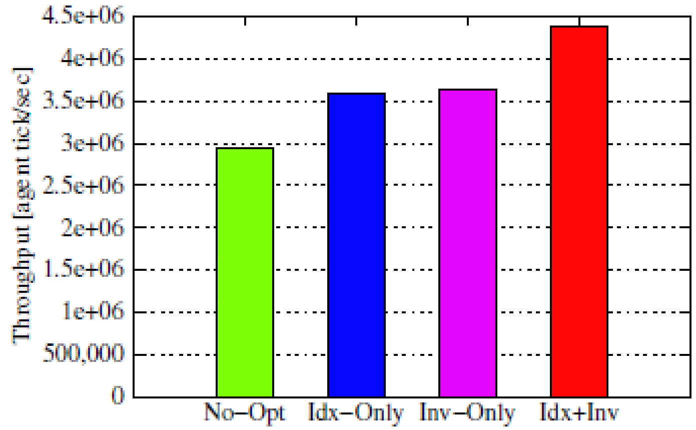

Figure 5: Predator: Effect Inversion

Traffic: Scalability

- Nearly linear scalability
- Sudden drop is an artifact of IP routing in the multi-switch configuration

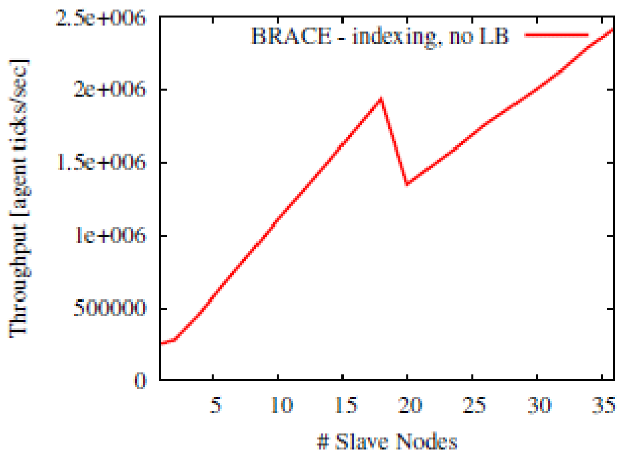

Figure 6: Traffic: Scalability

Fish: Scalability

- move in two different fixed directions
- Without load balancing:form in nodes at the extremes of simulated space,load at all other nodes falls to zero
- With load balancing:throughput increases linearly with the number of nodes

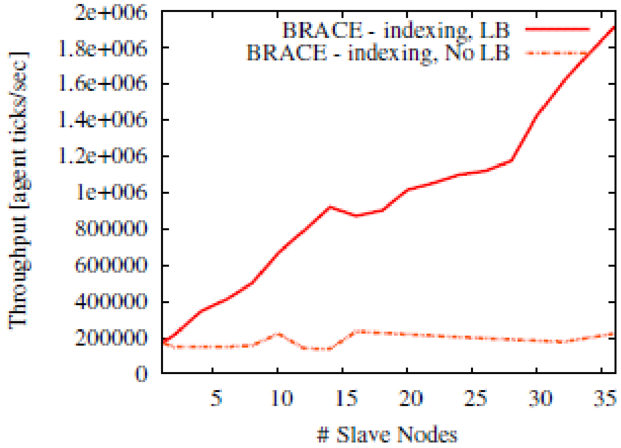

Figure 7: Fish: Scalability

Fish: Load Balancing

- With load balancing

  the time per simulation epoch is essentially flat

- With load balancing

  the epoch time gradually increases

  reflects all agents being simulated by only two nodes

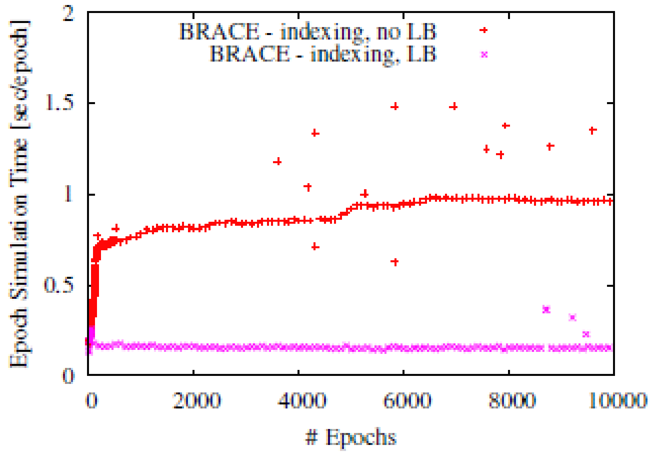

Figure 8: Fish: Load Balancing

Conclusions

- MapReduce can be used to scale behavioral simulations across clusters
- New programming environment for behavioral simulations
  - –Easy to program: Simulations in the state-effect pattern → BRASIL
    - -Hides all the complexities of modeling computations in MapReduce
    - -parallel programming from domain scientists
  - –Scalable: State-effect pattern in special-purpose MapReduce Engine → BRACE
    - -shared-nothing, in-memory MapReduce framework
    - -exploits collocation of mappers and reducers to bound communication overhead

Thanks!