A Gentle Introduction to Parallel and Distributed Simulation

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These **slides** and **extra information**

- These slides and some extra information can be found in my homepage and in the research group webpage:
  - http://www.cs.unibo.it/gdangelo
  - “Gabriele D'Angelo” → Google
  - http://pads.cs.unibo.it

Outline

- A little **background**
- **P**arallel **A**nd **D**istributed **S**imulation (**PADS**)
- New **challenges** of today and tomorrow
- **Functionality** and **limitations** of current PADS approaches
- In the search of **adaptivity**: the ARTÌS/GAIA approach
- **Conclusions**

Starting from scratch: **simulation**

- **"A computer simulation is a computation that models the behavior of some real or imagined system over time"**

  (R.M. Fujimoto)

- **Motivations:**
  - performance evaluation
  - study of new solutions
  - creation of virtual worlds such as online games and digital virtual environments
  - ...

Simulation: **more motivations**

- The system that needs to be **evaluated** can not be built (e.g. for cost reasons)
- **Testing** on an existing system can be very dangerous
- Some **stress testing** is actually impossible to perform
- Often many different solutions have to be **investigated** in order to choose the best one
- It can be used to support the **decision making** (e.g. real-time **what-if analysis**)

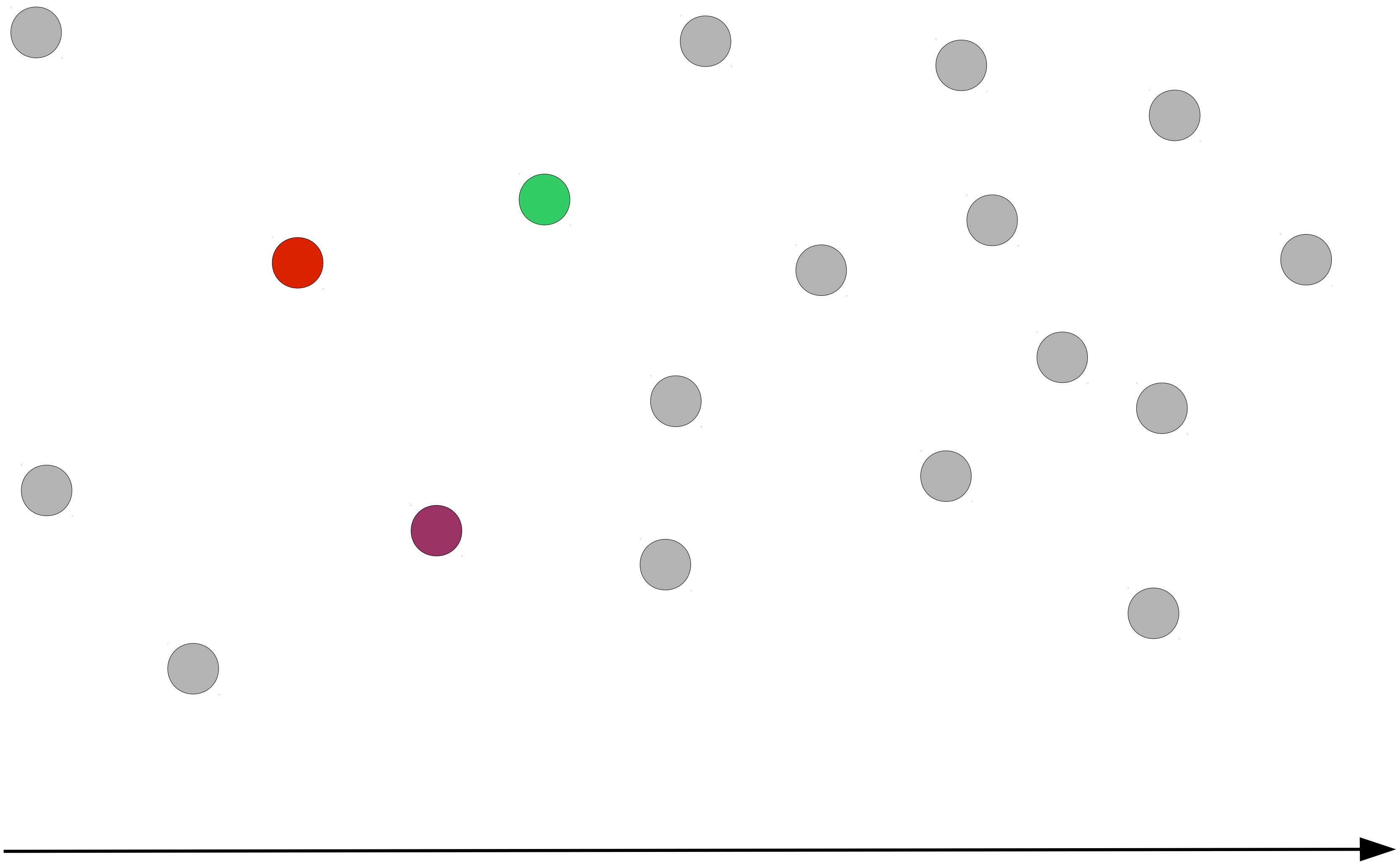
Simulation **paradigms**

- There is a strong demand for **more** and **more complex** systems
- A **huge number** of **simulation tools** following **different paradigms**
- A lot of issues on the **performance** of such software tools
- In the years, **many** different simulation **paradigms** have been proposed, each one with specific **benefits** and **drawbacks**
- There is not the "*correct way*" of doing simulations, there are many different ways. It is really a **case-by-case evaluation**

Discrete Event Simulation (DES)

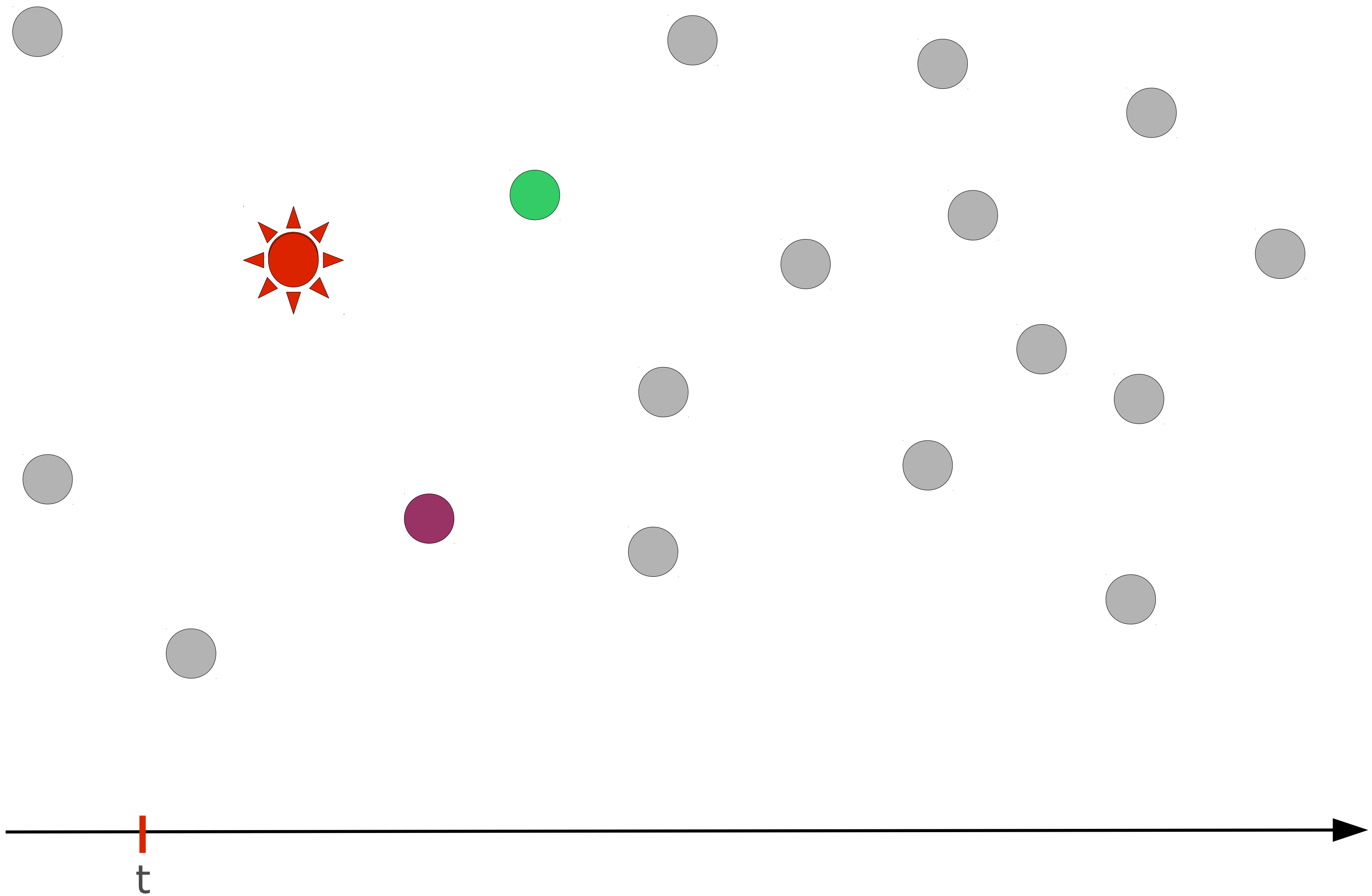
- The **state** of the simulated system is represented through a **set of variables**
- The key concept is the "**event**"
- An event is a **change in the system state** and it **occurs at an instant in time**
- Therefore, the evolution of a modeled system is given by a **chronological sequence of events**
- All is done through the **creation**, **delivery** and **computation** of events
- The computation of an event can **modify some part of the state** and **lead to the creation of new events**

DES: a simple example



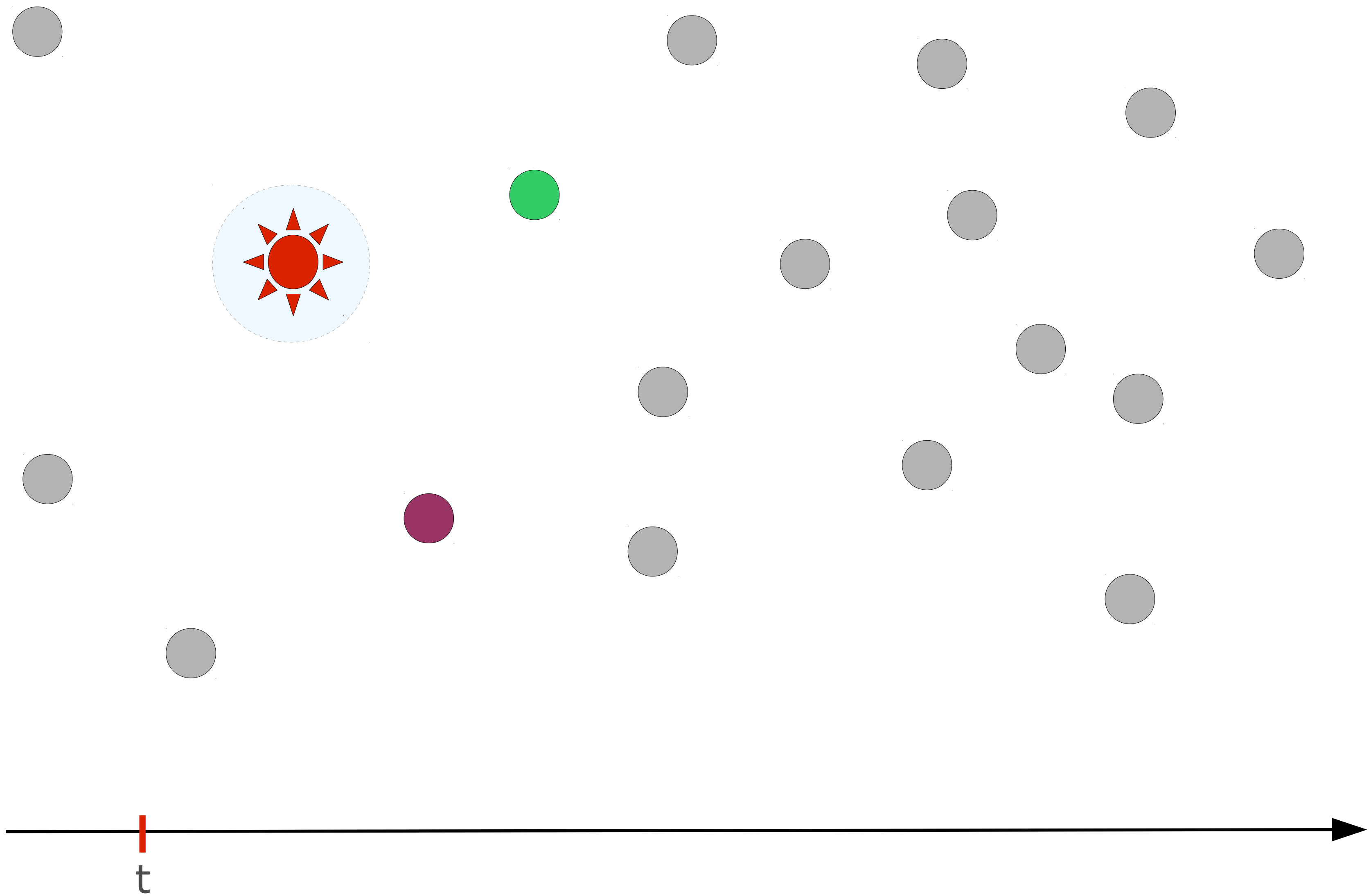
1) *A set of mobile wireless hosts*

DES: a simple example



2) *At time **t** the red node starts transmitting*

DES: a simple example



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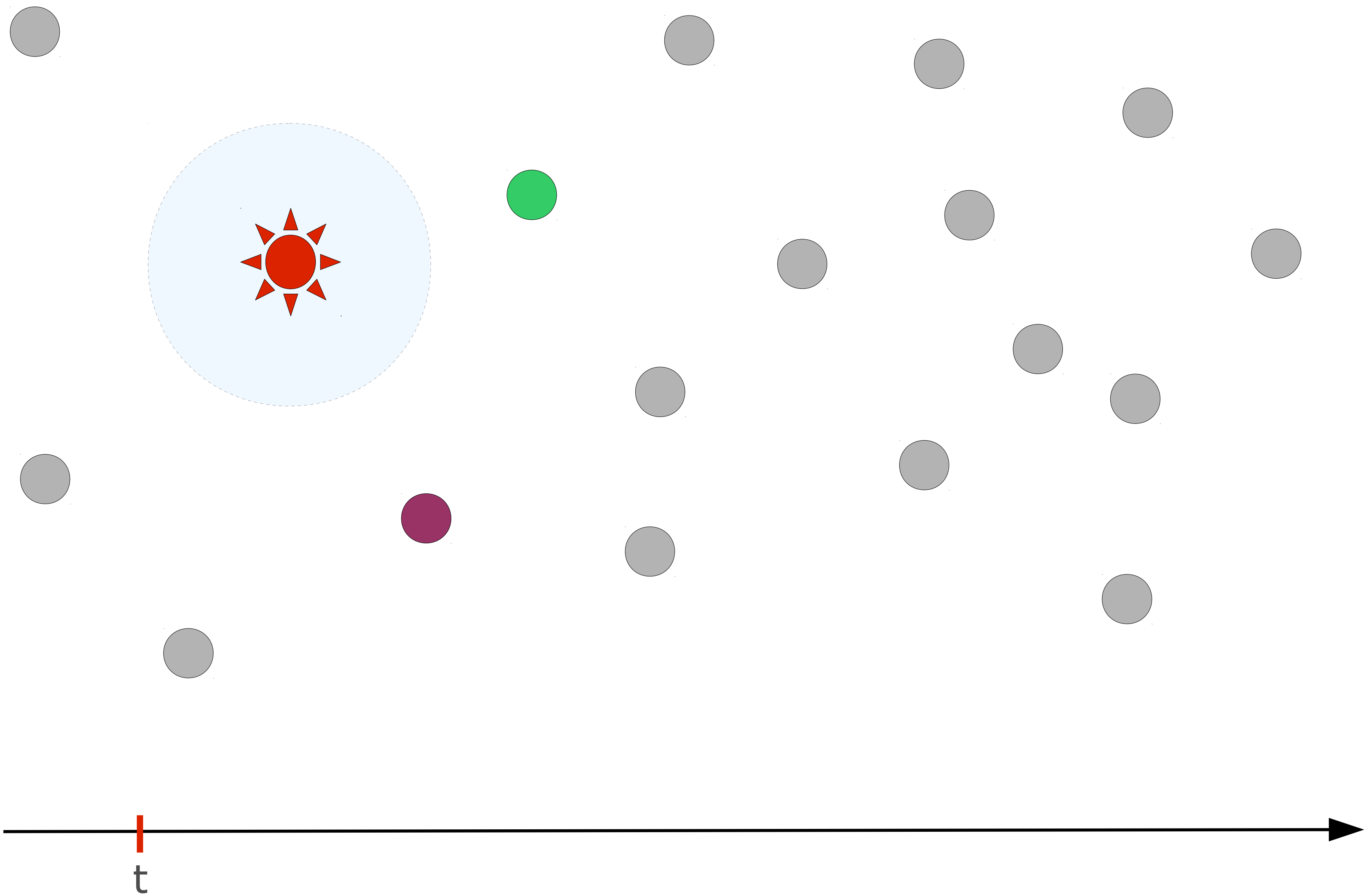
DES: a simple example



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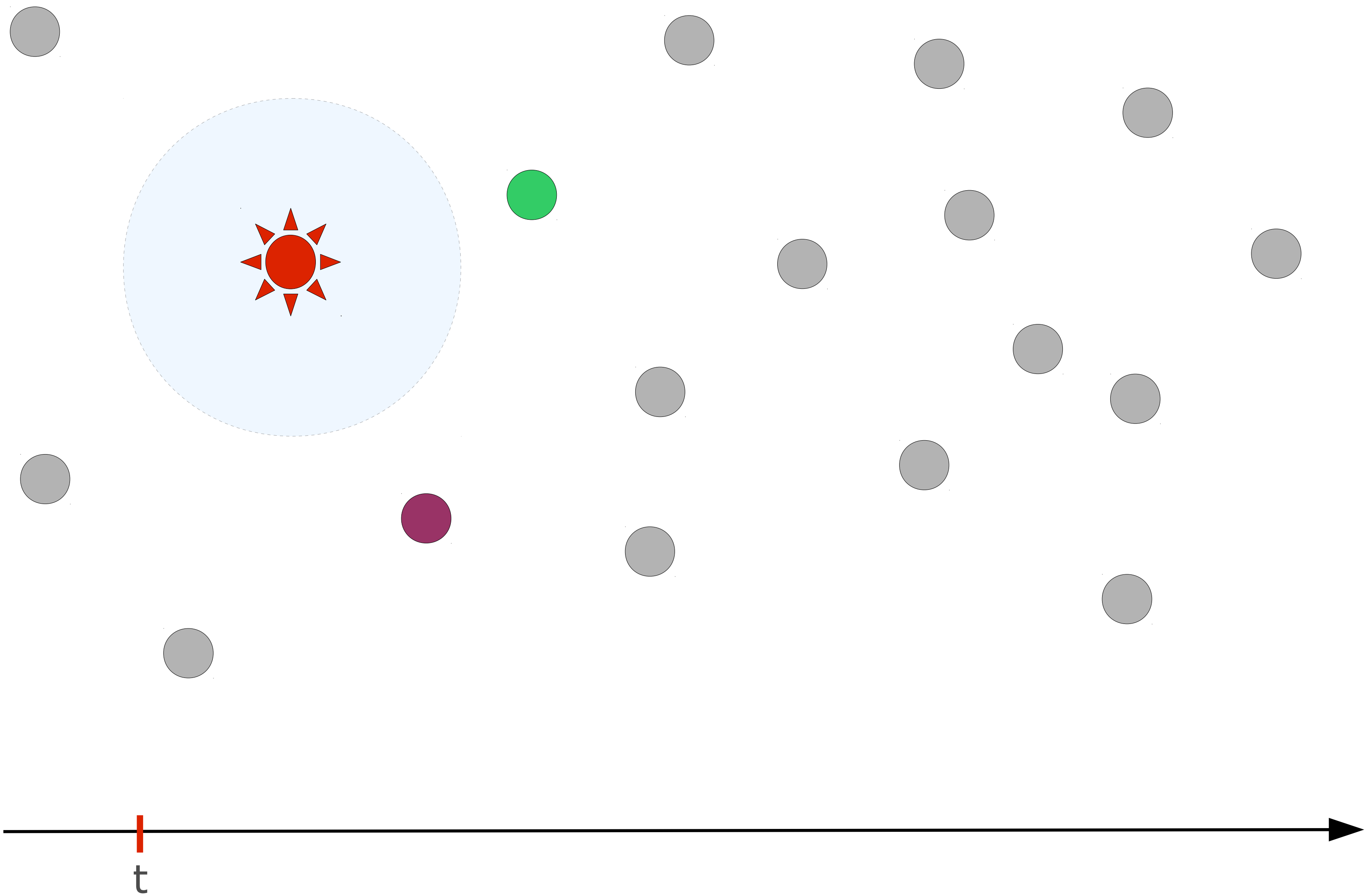

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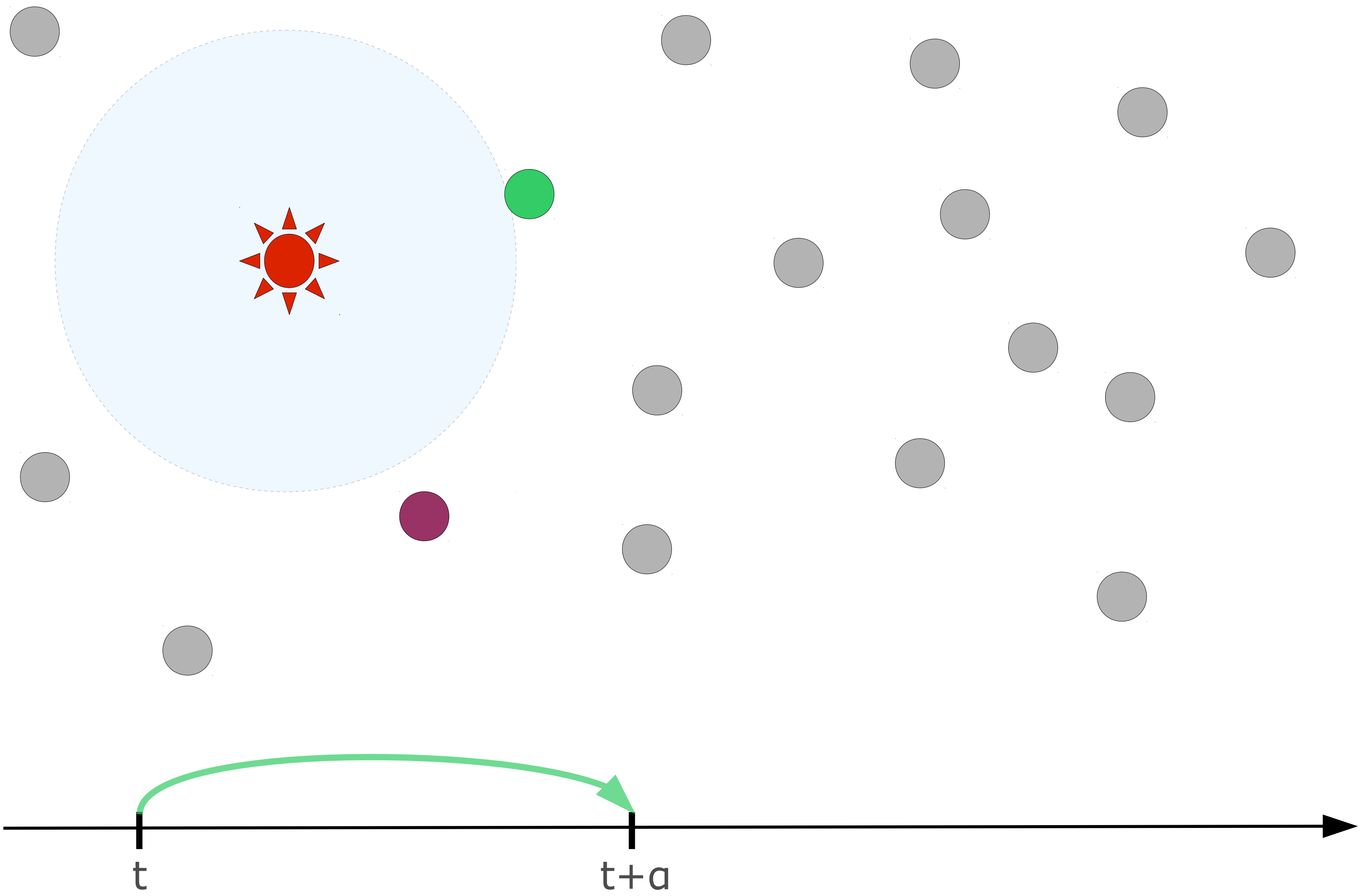
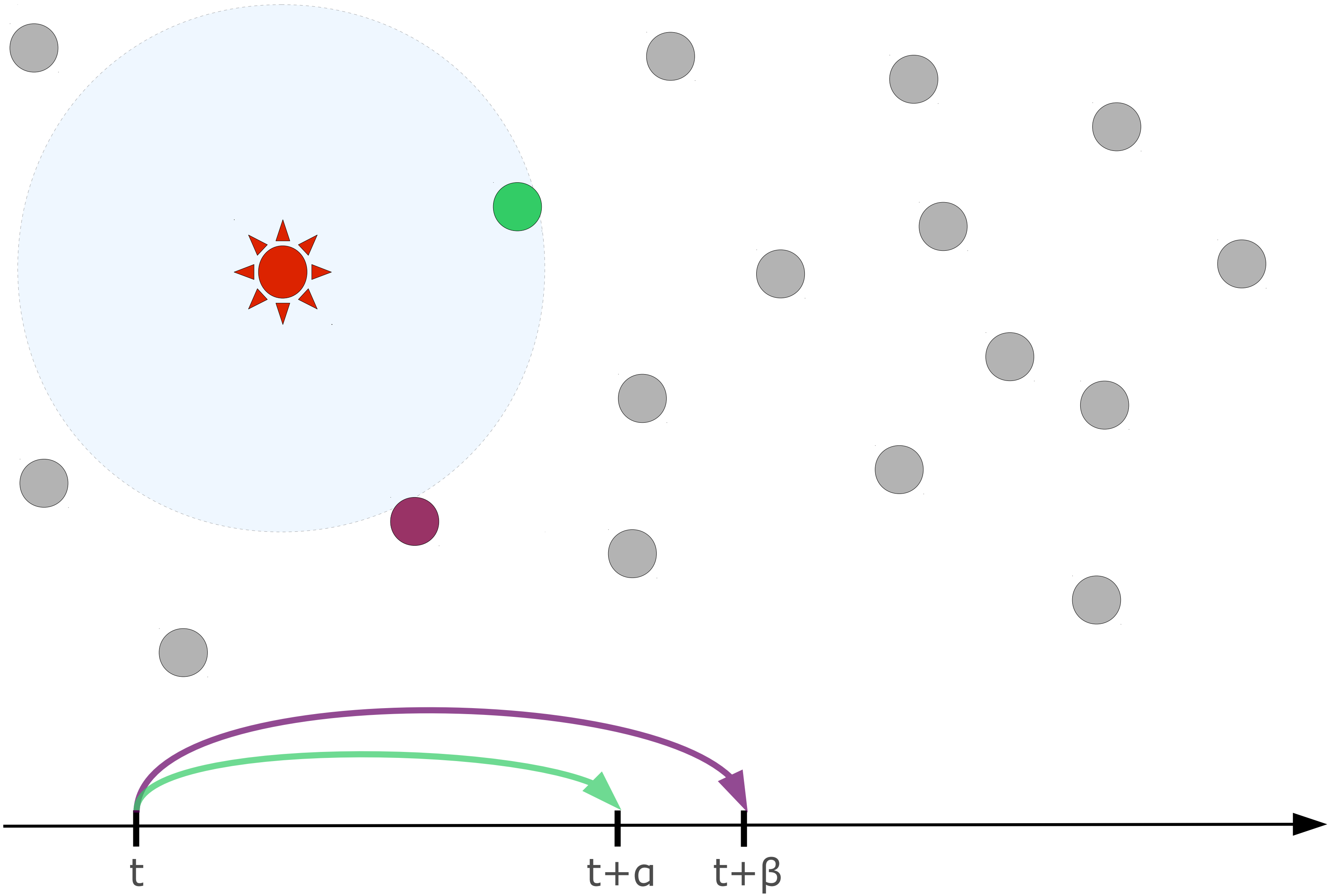
DES: a simple example



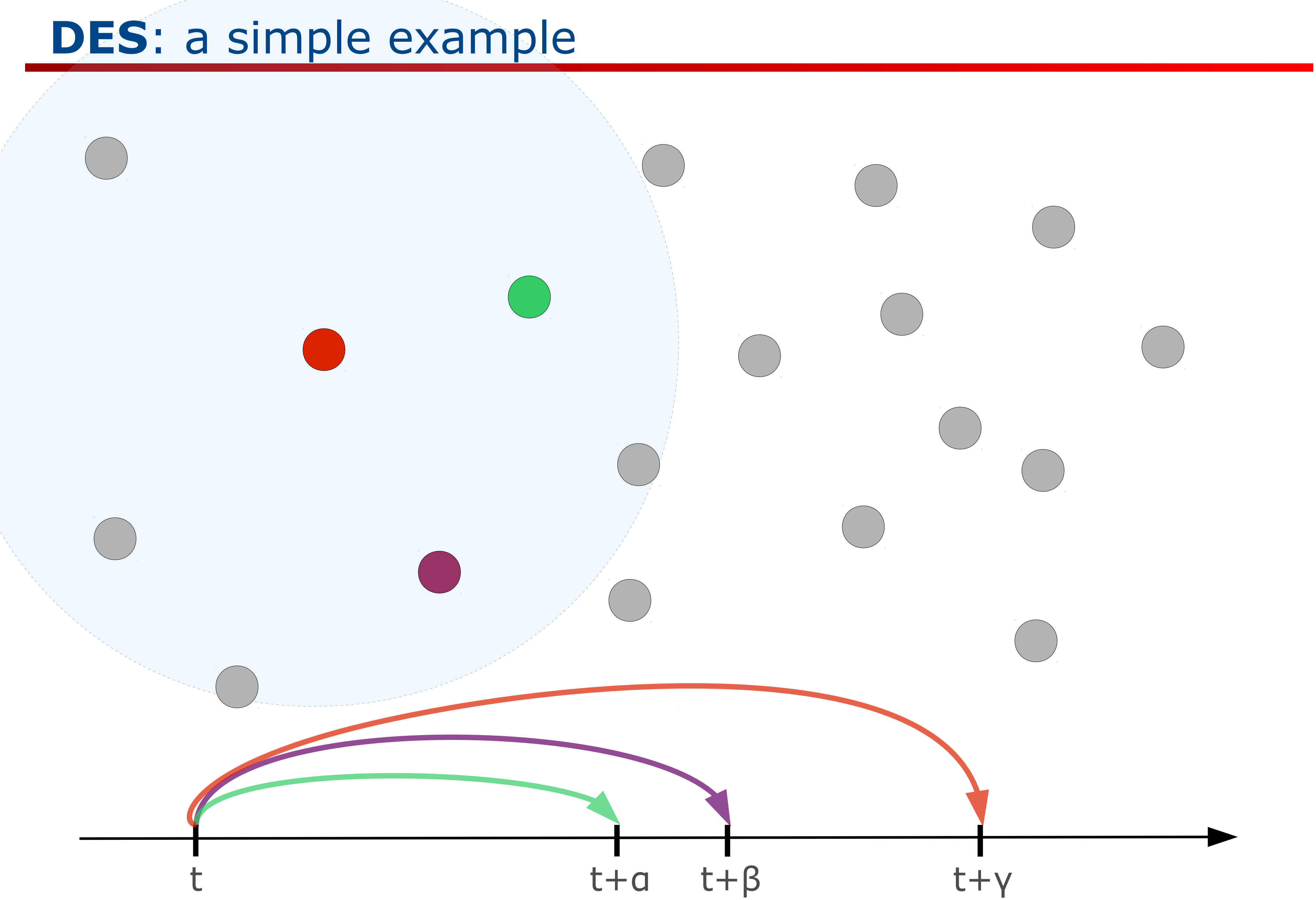
3) *At time **t+a** the green node starts receiving*

DES: a simple example



4) *At time **t+β** the dark violet node starts receiving*

DES: a simple example



5) *At time **t+γ** the red node stops transmitting*

Implementation of DES

Data structures:

- a set of **state variables** *(to describe the modeled system)*
- an **event list** *(pending events that will be processed in future)*
- a **global clock** *(the current simulation time)*

Simulator:

- the simulator is mostly made by a set of "**handlers**", each one managing a different event type

Notes:

- events are not produced in (simulated) time order but **have to be executed in non-decreasing time order**
- in fact, the **event list** is a **priority queue**
- the list based implementation is very inefficient
- heap-based solutions are widely used

DES on a **single CPU**: **sequential simulation**

- All such tasks are accomplished by a **single execution unit** (that is a CPU and some RAM)
- **PROS**: it is a **very simple approach**
- **CONS**: there are a few **significant limitations**
  - the **time** required to complete the simulation run
    - *how fast is a single CPU?*
    - *in some cases results have to be in real time or even faster!*
  - if the model is quite large and detailed the RAM is not sufficient: it is **not possible to model some systems**
- **This approach does not scale!**

Parallel **D**iscrete **E**vent **S**imulation (**PDES**)

- **Multiple interconnected** execution units (**CPU**s or **hosts**)
- Each unit manages **a part of the simulation model**
- Very large and complex models can be represented using the resources **aggregated** from many execution units
- Each execution unit has to manage a **local event list**
- **Locally generated events** may have to be **delivered to remote execution units**
- All of this needs to be carefully **synchronized**
- "**Concurrent events**" can be **executed in parallel**, this can lead to a significant **speedup of the execution**

Going **Parallel**: **PDES**

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- "**Concurrent events**" can be **executed in parallel**, this can lead to a significant **speedup of the execution**

It means that the model has to be partitioned and each part allocated on a different CPU.

Is that easy?

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Parallel And Distributed Simulation (PADS)

- **"Any simulation in which more than one processor is employed" (K.S. Perumalla)**
- This is a very simple and general definition, there are many different "flavors" of PADS
- A lot of **good reasons for going PADS**:
  - **scalability**
  - **performance** (obtaining the results faster)
  - to model **larger** and **more complex** scenarios
  - **interoperability**, to integrate commercial off-the-shelf simulators
  - **composability** of different simulation models
  - to integrate simulators that are **geographically distributed**
  - **Intellectual Property** (IP) protection
  - ...

Parallel And Distributed Simulation (PADS)

- There is **no global state**: this is the key aspect of **PADS**
- A **PADS** is the **interconnection** of a set of **model components**, usually called **Logical Processes** (**LP**s)
- Each **LP** is responsible to manage the evolution of only **a part of the simulation**
- Each **LP** has to interact with other **LP**s for **synchronization** and **data distribution**
- In practice, each **LP** is usually executed by a **processor** (or a **core** in modern multi-core architectures)
- The **communication** among **LP** (and the **type of network** that interconnect the processors) is of main importance
- It strongly affects simulator characteristics and **performance**

Parallel, distributed or… **mixed**?

- What is **parallel** simulation and what **distributed**?
- The difference is quite elusive but with some importance
- We choose a very simple definition from the many that are available
- **Parallel**: the processors have access to some **shared memory** or a **tightly coupled** interconnection network
- **Distributed**: **loosely coupled** architectures (e.g. **distributed memory**)
- Real world execution architectures are more **heterogeneous**
- **For example**: **a)** *LAN-based clusters of multi-CPU (and multi-core) hosts*, **b)** *a mix of local and remote resources (e.g. Cloud Computing)*

On the (lack of) **global state** and its **consequences**

- In a sequential simulation there is a global state that represents the **simulated system at a given time**
- In a **PADS**, such a global state is **missing**
- There are some very interesting consequences
- The model has to be **partitioned** in **components** (the **LP**s)
- In a parallel/distributed architecture **synchronization** mechanisms have to be implemented
- **Data is produced locally** (within the **LP**) but can be of interest to other parts of the simulator (other **LP**s): **data distribution** mechanisms
- All these are **main problems of PADS**: we need to introduce them a little more in detail

Partitioning: creating and allocating parts

- Each **LP** is responsible for the management of **a part of the simulated model**
- In some cases the partitioning follows the **structure** and the **semantics** of the simulated system
- In other cases is **much harder**, for example if the system is **monolithic** and hard to split in parts
- **Many different aspects** have to be considered in the partitioning process
- For example:
  - **minimization** of **network communication**
  - **load balancing** of both **computation** and **communication** in the execution architecture

Synchronization: on the correct order of events

- Some kind of **network** interconnects the **LP**s running the simulation
- Each **LP** is executed by a different **CPU** (or **core**), **possibly at a different speed**
- The **network** can **introduce delays** but we assume that the communication is reliable (e.g. TCP-based communications)
- The results of a **PADS** are **correct** only if its outcome is **identical** to the one obtained from the corresponding **sequential** simulation
- **Synchronization mechanisms** are used to **coordinate** the **LP**s: **different approaches are possible**
- This task usually has a **very relevant cost**

Data distribution: on the dissemination of information

- Each component of the simulator will produce **state updates** that are possibly **relevant for other components**
- The distribution of such updates in the execution architecture is called **data distribution**
- For overhead reasons **broadcast can not be used**
- The goal is to **match** data **production** and **consuming** based on **interest criteria**
- Only the **necessary** data has to be **delivered** to the **interested** components
- There are both **communication** and **computation** aspects to consider
- Data distribution also has to be properly synchronized

In-depth: **synchronization**, **causal ordering**

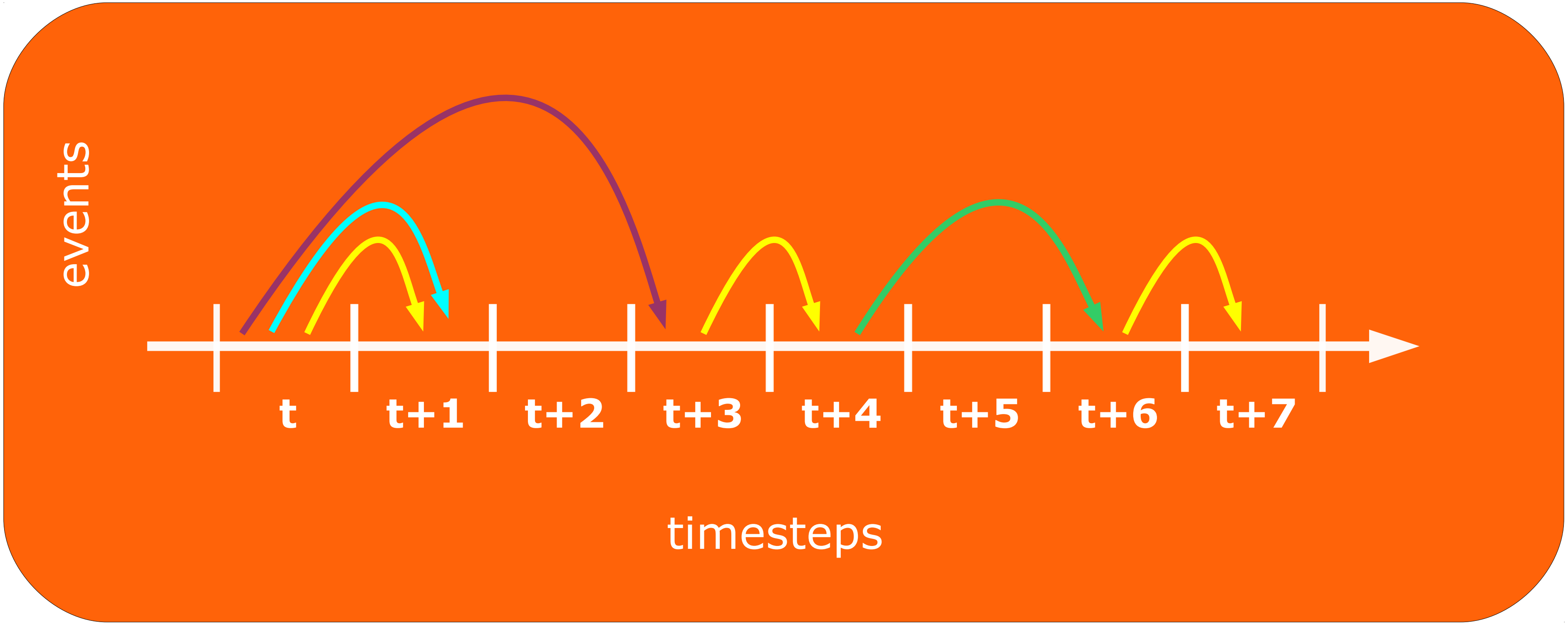
- Implementing a **PDES** in a **PADS** architecture requires that all generated events have to be **timestamped** and delivered following a **message-passing** approach
- Two events are said to be in **causal order** if one of them **can have some consequences on the other**
- The execution of events in **non causal order** leads to **causality errors**
- In a sequential simulation it is easy avoid causality errors given that there is a single ordered pending event list
- But in a **PADS** this is **much harder**!
- In this case the goal is to:
  - *execute events **in parallel**, as much as possible*
  - *do not introduce **causality errors***

In-depth: **synchronization**, **approaches**

- The most studied aspect in PADS because of its importance
- Many different approaches and variants have been proposed, with some simplification **three main methods**:
  - **time-stepped**: *the simulated time is divided in* ***fixed-size timesteps***
  - **conservative**: ***causality errors are prevented,*** *the simulator is built to avoid them*
  - **optimistic**: *the* ***causality constraint can be violated*** *and errors introduced. In case of causality violations the simulator will fix them*
- In the following we will see more in deep each of them

In-depth: **synchronization**, **time-stepped**

- The **simulated-time** is divided in **fixed-size timesteps**
- Each **LP** can proceed to the **next timestep** only when all other **LP**s have **completed the current one**
- It is a **discretization** of time, that is clearly continuous



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- Each **LP** can proceed to the **next timestep** only when all other **LP**s have **completed the current one**
- It is a **discretization** of time, that is clearly continuous
- The **timestep size** can be chosen by the model developer but **strongly affects performances** *(smaller steps equals to more synchronization points)*
- The main **advantage** is its **simplicity**: simple to implement and quite easy to understand for the simulation developer
- **Drawbacks**: **unnatural paradigm** for some systems to model, in some cases the step needs to be very small *(e.g. in the simulation of media access control protocols)*

In-depth: **synchronization**, **conservative**

- The **goal** of this approach is to **prevent causality errors**
- **Before processing each event** (e.g. with timestamp ***t***), the **LP** has to decide if the **event** is "**safe**" or "**not**"
- It is **safe** if, **in future**, there will be no **events with timestamp less than *t***
- Remember that, in this case, there cannot be **causality errors** to be fixed, the simulator has to **avoid them *a priori***
- If all **LP**s process event in **timestamp order** then the **PADS** results will be **correct**
- A **mechanism** to determine **if and when an event is safe** is needed

In-depth: **synchronization**, **CMB**

- The **C**handy-**M**isra-**B**ryant (**CMB**) is a widely used algorithm for **conservative synchronization**
- **LP**s can only process events that are "**safe**"
- In many cases the **LP** will have to **stop**, **waiting** to get enough information to decide if an event is "**safe**" or **not**
- The **deadlock** is **avoided** using **NULL messages**
- A **NULL message** is an **event** with **no semantic content**
- It is necessary only for **spreading information on synchronization**
- Every **LP**, each time a new event is processed, has to send as many **NULL messages** as the number of **LP**s at which it is connected to

In-depth: **synchronization**, **optimistic**

- The **LPs** are **free to violate** the **causality constraint**
- They can **process events in receiving order** (vs. timestamp order)
- There is **no *a priori* attempt** to detect "**safe**" events and to **avoid causality violations**
- In case of violation this will be **detected** and appropriate mechanisms will be used to **go back to a prior state** that was correct
- The main mechanism is the **roll back of internal state variables** of the **LP** in which happened the violation
- If the **error has propagated** to other **LPs** then also the **roll back has to be propagated** to all the affected **LPs**

In-depth: **synchronization**, **Time-warp**

- The Jefferson's **Time Warp** mechanisms implements optimistic synchronization
- Each **LP** process all events that it has received up to now
- An event is "**late**" if it has a timestamp that is smaller that the current clock value of the **LP** (that is the timestamp of the last processed event)
- The violation of **local causality** is fixed with the **roll-back** of all the **internal state variables** of the simulated model
- Likely the violation has propagated to other **LP**s
- The goal of "**anti-messages**" is to **annihilate** the corresponding unprocessed events in **LP**s pending event list or to cause a **cascade of roll-backs** up to a **globally correct state**

In-depth: **synchronization**, **what is best?**

- All these approaches have been deeply investigated and many *variants / tunings* have been proposed
- **What is the best synchronization approach for PADS?**
- Very hard question, the **performance** of such methods **heavily depends on many factors**:
  - *simulation model*
  - *the execution environment*
  - *the specific scenario*
- **Forecasting** the **performance** of **PADS** is **very hard**, it depends on **too many factors**, some **static** and some **dynamic**, some **known** and **many unknown** in advance *(e.g. the runtime conditions of the execution architecture)*

PADS: software tools

- There are many software tools for the implementation of **PADS**
- Some of them are compliant with the **High Level Architecture** (**HLA**) **IEEE 1516 IEEE standard**: *RTI NG Pro*, *Georgia Tech FDK*, *MÄK RTI*, *Pitch RTI*, *CERTI Free HLA*, *OpenSkies Cybernet*, *Chronos* and the *Portico Project*
- Many others are more focuses on **performance** or other aspects such as **extensibility** or testing of **new features**.
  For example: *μsik*, *SPEEDES* and *PRIME*
- In the next part of the tutorial we will discuss if current **PADS** technologies are ready for the **new challenges** of today and tomorrow

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New challenges: what's next?

- Evolution in computing technology is fast and often confusing
- But it is possible to identify some **characteristics** and **trends**
- Frequent **updates in hardware** but **software is slow in supporting them**
- On the other hand, **software** is **limited** by **hardware characteristics**
- For many years, 32 bits processors have limited the max amount of memory of sequential simulators
- Now with 64 bits CPUs memory remains an issue only with huge simulations

New challenges: some existing and new trends

- The so called "**MHz race**" in CPUs has **slowed down**
- **Multi-core CPUs** are now available at bargain prices
- Only few users have access to **High Performance Computing** facilities *(i.e. supercomputers and dedicated clusters)*
- Many are willing to use **Commercial Off-The-Shelf** (**COTS**) hardware that is also **shared with other tasks** *(e.g. desktop PCs or underloaded servers)*
- **Outsourcing** the **execution of simulations** is the next big step in this direction

New challenges: cloud computing

- **Cloud computing** is a model for providing **on-demand** network access to a **shared pool** of computing resources
- Such resources can be **provisioned** and **released quickly** and with minimal management effort
- For many reasons cloud computing is becoming mainstream
- Implements the "**pay-as-you-go**" approach: virtual computing environments in which you **pay only for capacity that you actually use**
- The resources are obtained from a shared pool and provided by **commercial service providers**

New challenges vs. **existing software tools**

- **Available simulators** are **unable to cope** with such changes in the execution environment
- Often they **do not exploit** all the **available resources**
- That means that are **too slow** in obtaining the **results**
- The effect is that users are more and more encouraged to **oversimplify the simulation models**
- That's a very **risky move**...
- In the next slides we'll discuss more in deep a couple of these challenges

New challenges: many cores

- **Entry level CPUs** provide ***2*** or ***4*** **cores** but processors with ***16*** cores are already available on the market
- **CPUs** with **100** cores are announced for the end of this year
- This is a **big change in the execution architecture** and will **not be transparent** to simulation users
- **Sequential simulators** are, for the most part, **unable to exploit more than one core**
- This means that **PADS** techniques will be **necessary** even to run simulations on a **desktop PC**

New challenges: many cores

- Even if assuming that all **cores** are **homogeneous** *(and that is not always true)*, the simulation model has to be **partitioned** in **more and more LPs**

- The **partitioning** is a **complex task** and increasing the number of cores it becomes **harder** and **harder**

- The **load of each core** has to be **balanced** and the **communication** among cores has to be **minimized**

- Who is in charge of the partitioning has to predict *a priori:*
  - *the **behavior** of the **simulated model***
  - *the **load** of the **execution architecture***

New challenges: many cores

- All **static approaches** are **suboptimal**: the **runtime conditions** are **variable**
- Who is in charge of **partitioning**?
  - *currently, the **software** is **unsuitable** to perform this task*
  - *it is still in charge of the **simulator user**!*
- It is clear that **this approach does not scale**!
- Most simulation users are not willing to become experts of **PADS** or computing architectures
- Their goal is to **obtain results as fast as possible** and **with the least effort**
- It is clear that it should be a **software task**!

New challenges: the public cloud

- Everything is going "**on the cloud**". Why simulation is **not**?
- Please do not confuse the **private cloud** and the **public cloud** infrastructures, they are very different!
- The big goal is to follow the "**everything as a service**" paradigm and to **rent the resources** for running simulations
- On the market there are many providers of cloud services *(e.g. Google, Amazon, Microsoft...)*
- You **pay only for the rented resources** and you can **increase** or **decrease** them **dynamically**
- This is great for small or medium size firms: **no more investments in hardware**!

New challenges: the public cloud

- A public cloud environment can be **very dynamic**, **variable** and **heterogeneous**
- For example, the **virtual instances** providing the services can be located in **different data centers**, with **different Service Level Agreements** and from **different providers**
- Under the **PADS** viewpoint, also in this case **it is a matter of partitioning**
- This is an even **more complex version** of the partitioning problem
- But we have already seen that **current software tools** are **unable** to cope with this problem

New challenges: the public cloud on steroids

- Let's go on with our vision of "**simulation-as-a-service**"
- The price of cloud computing services is highly dependent on aspects such as **reliability** and **guaranteed performance**
- It is a pricing model based on the assumption that all customers have the **same requirements**
- **PADS** tools could (automatically) rent very **inexpensive** (and **low reliability**) cloud services
- The **middleware** running the **PADS** will be in charge of **coping with faults**
- This can be "easily" done adding some degree of **replication**
- This is a further extension of the partitioning problem

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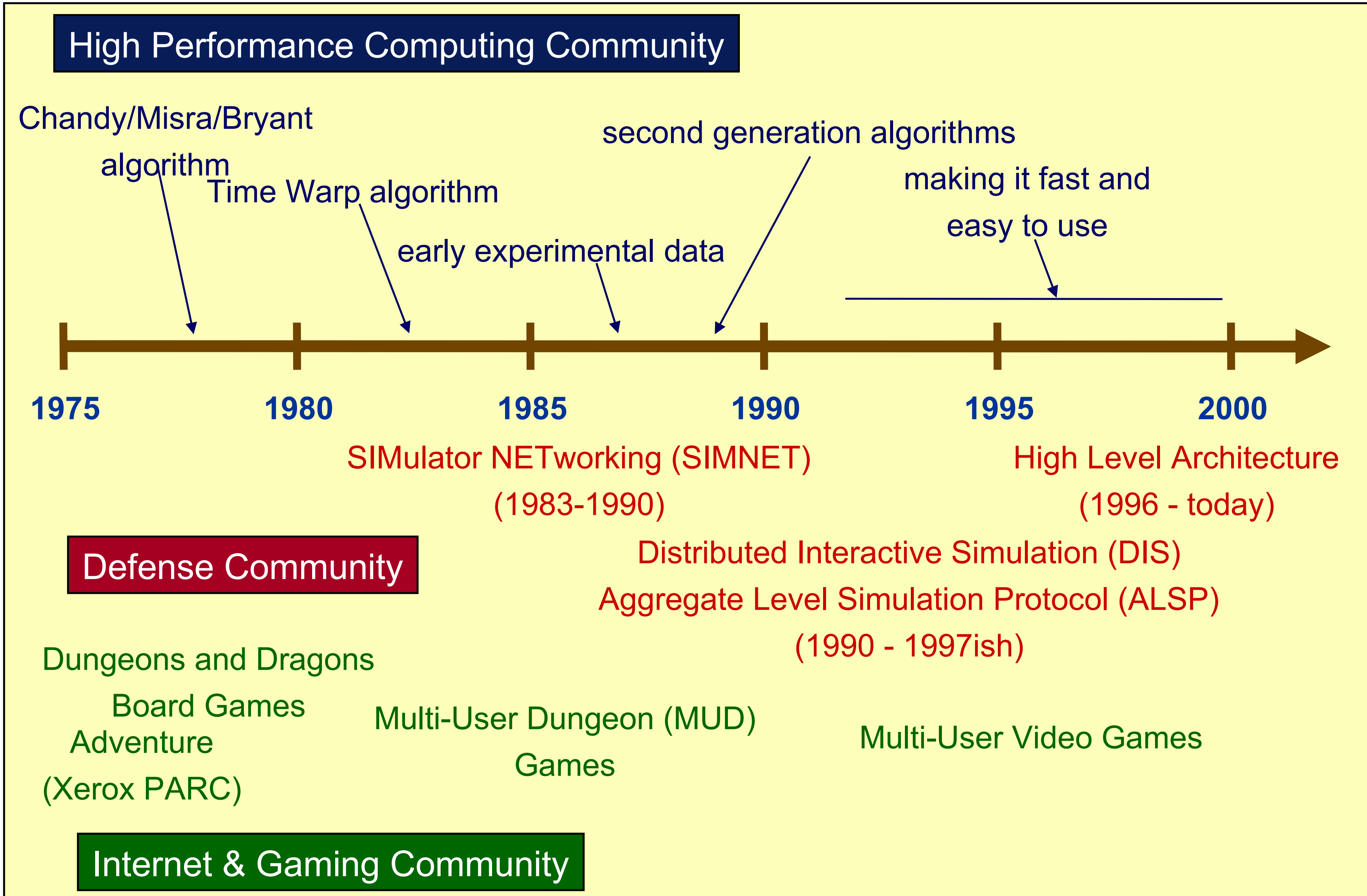
Is **PADS** ready for **primetime?**

- The **complexity** of studied systems is **increasing**
- Many would expect a **broad application** of **PADS** techniques
- **Is that happening? No, it is not!**
- Many users are **unwilling** to dismiss the “old” (**sequential**) tools and switch to more modern ones
- Even if there is a **strong demand** for **scalability** and **faster execution speed**
- **What is missing?**
- There is obviously a problem that should be more clearly defined and investigated

Historical perspective on **PADS**



Richard M. Fujimoto, tutorial, 2000

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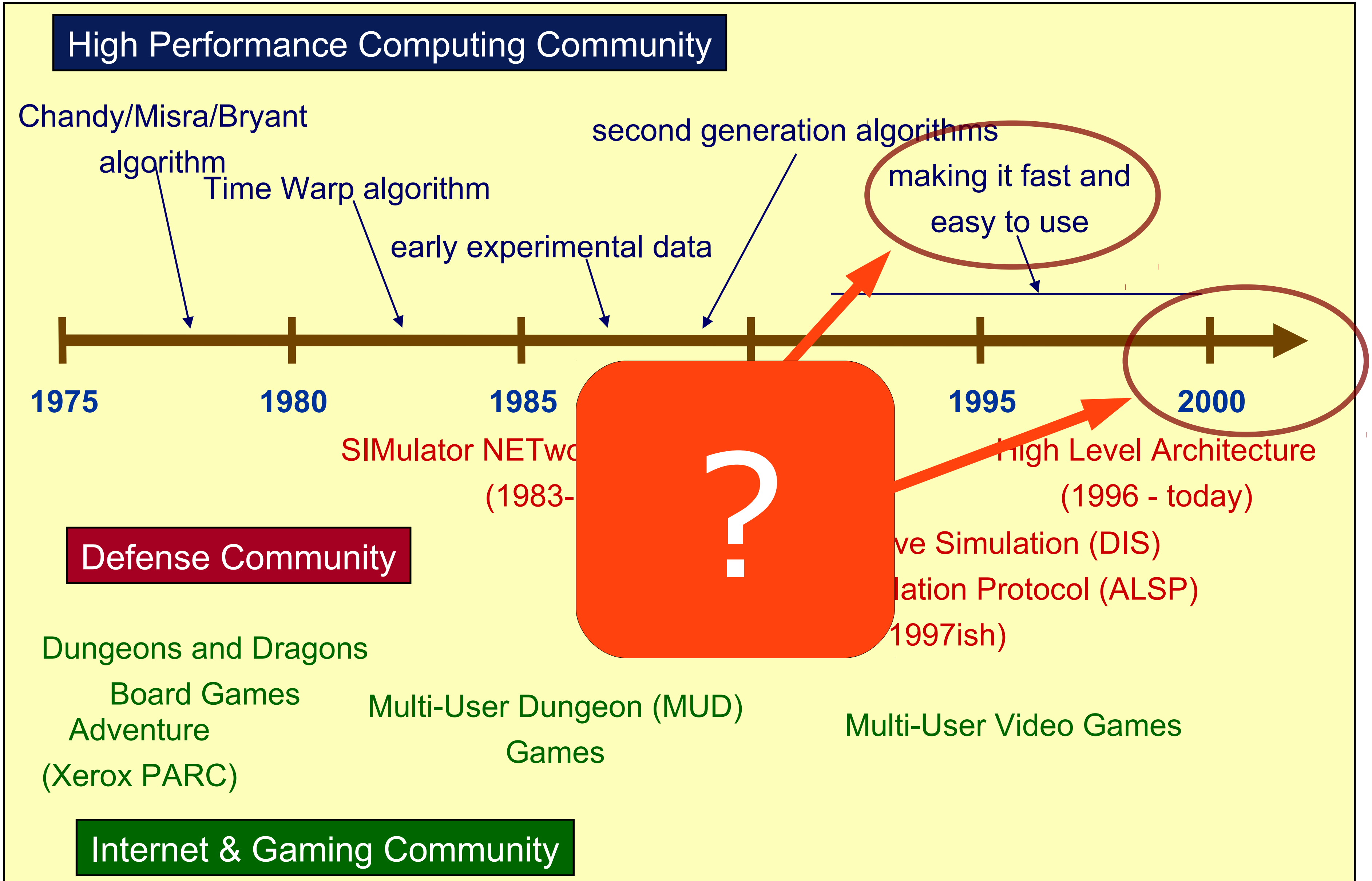


Richard M. Fujimoto, tutorial, 2000

PADS: what happened in the last two decades?

- Two **main research goals**:
  - *make it **fast***
  - *make it **easy** to use*
- A lot of work in synchronization and data dissemination management has been done

  → **in some conditions** PADS is very fast

  … properly partitioned model, appropriate synchronization algorithm, homogeneous execution architecture …
- What about **usability**?

  PADS does not work straight out of the box
- The level of **knowledge** modelers are required is still too high, some aspects are **hard to manage** and **understand**

PADS: what is the **better choice**?

- In some cases **PADS** techniques are necessary, in other are not *(e.g. when **PADS** is slower than sequential)*
- Each time there is something to simulate, the main question should be: **what is the better choice?**

  … sequential, parallel, distributed, conservative, optimistic …
- The execution environments are becoming much more heterogeneous:
  - *multi-core CPUs (… many core CPUs)*
  - *clusters, private and public clouds*
- Up to now, the whole problem is left to the simulation model developer
- **It feels like PADS tools are for initiates**

Why is it so difficult to decide what is best?

- Even the **sequential** or **PADS** choice is **hard to make**!
- It depends on **dynamic parameters** in **all the logical layers** of the architecture *(e.g. hardware, software)*
- All those parameters need a **case-by-case evaluation**
- Furthermore, they can change within the simulation runs:
  - ***semantic*** *of the simulation model*
  - *variable* ***background load*** *in the execution architecture*
- In many cases all such **aspects** and **parameters** are **not known** *a priori*

PADS: usability (lack of)

- The **user** of simulation tools should be able to **focus on modeling** and **analysis** of results
- Very often the modeler uses a **different tool** if he wants to build a **sequential** simulation or a **PADS** one
- What happens if after implementing a sequential one he discovers that it is **too slow**?
- Now many **key aspects** are left to the simulation developer and that's **clearly wrong**!
- In 2000 it has been approved the **IEEE 1516 standard** for distributed simulation called **H**igh **L**evel **A**rchitecture (**HLA**)
- **HLA** supports optimistic synchronization but a significant part of the support mechanisms is left to the simulation developer

PADS: cost assessments, the need for new metrics

- The **amount of time** needed for completing a simulation run is called **W**all-**C**lock-**T**ime (**WCT**)
- The **WCT** has always been the **main metric** to evaluate the **efficiency of simulators**
- This can be right in classic execution architectures but **it is not** when the resources are obtained following the "***pay for what you use***" scheme *(e.g. public cloud)*
- A **more complex evaluation** has to be done:
  - *how much time the user can **wait for the results**?*
  - *how much he **wants to pay** for running the simulation?*
- Are the current **PADS** algorithms and mechanisms suitable for this new evaluation metric?

PADS: cost assessments, the need for new metrics

- As seen previously the **C**handy-**M**isra-**B**ryant (**CMB**) algorithm is often used for implementing **conservative** synchronization
- To avoid **deadlocks** it introduces **artificial events** *(i.e. without any semantic content)*
- The **number** of such events can be **very high**
- Despite of many optimizations the amount of **extra communications** is often **prohibitive**
- In a distributed execution environment such as the cloud in which the available **bandwidth** is **limited** (and **costly**) this approach is **not very promising**
- What about optimistic synchronization? Is it better?

PADS: cost assessments, the need for new metrics

- **Computation** is much **faster** (and **cheaper**) than **communication**
- This **assumption** is at the **basis** of **optimistic synchronization**
- This means that, in a **PADS**, the **CPU** will be often **idle waiting** form some data from the network
- Therefore it is better to proceed with the computation and roll-back if something has gone wrong *(e.g. a causal violation)*
- Also this approach is **not well suited** for the "**pay for what you use**" model
- In optimistic simulations a large part of the computation can be thrown away due to roll-backs

PADS: in search of performance

- Let's assume that **costs are not a problem** and that the goal is to **obtain the results as fast as possible**
- Continuing to focus on **synchronization**, the traditional algorithms are **fast** when run in a **public cloud**?
- What level of **performance** we can expect?
- The answer is quite simple: using the traditional approaches the **obtained results can be poor**
- What is the **problem**?

PADS: in search of performance

- Both in **timestepped** and **conservative** approach a **slow LP** would become the **bottleneck** of the whole simulation
- The real problem is the **lack of adaptivity**: the **static partitioning** of the simulated model has big drawbacks
- With **optimistic** it is **even worse**
- E.g. **Jefferson's timewarp** is well-known to have good performance if all **LP**s have the **same execution speed**
- This assumption is very **unrealistic** in public environments

Outline

- A little **background**
- **P**arallel **A**nd **D**istributed **S**imulation (**PADS**)
- New **challenges** of today and tomorrow
- **Functionality** and **limitations** of current PADS approaches
- In the search of **adaptivity**: the ARTÌS/GAIA approach
- **Conclusions**

How: on the adaptive approaches

- **Warning**: the "silver bullet" does not exist, even in simulation
- In our vision, all starts with the **partitioning problem**: *decomposing the simulation model into a number of components and properly allocating them among the execution units*
- **Constraints**: the **computation load** has to be kept balanced while the **communication overhead** has to be minimized
- Given that the runtime conditions are largely **unpredictable** and the environment is **dynamic** and very **heterogeneous**, all static approaches are not adequate

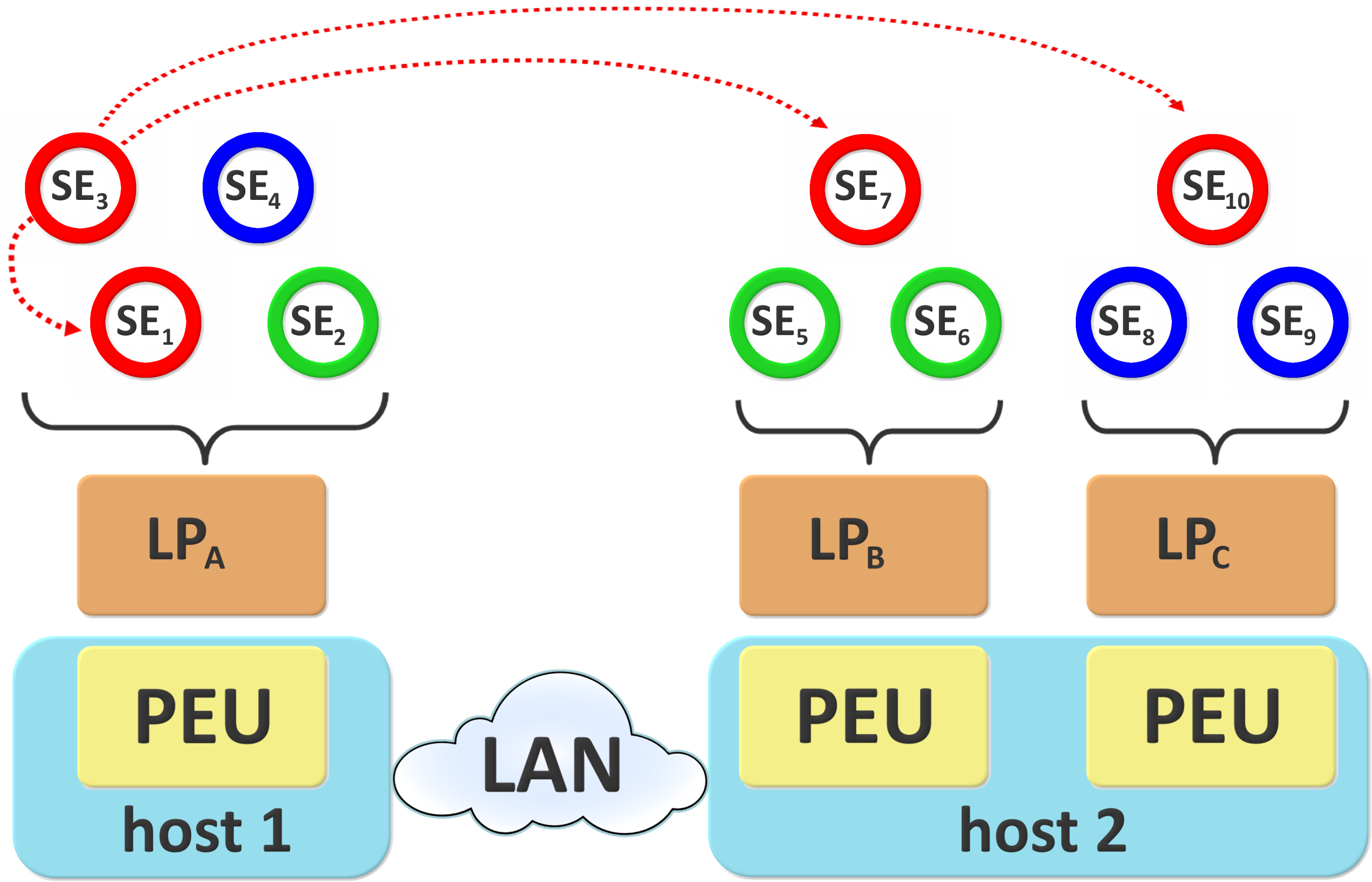
Migration-based **adaptive partitioning**

- The simulated model is divided into very small parts (called **Simulated Entities**, **SE**s)
- Each **SE** is a tiny piece of the simulated model and interacts with other **SE**s to implement the model behavior
- It is some sort of **Multi Agent System** (**MAS**)
- Each **node** (called **Logical Process, LP**) in the execution architecture is the container of a dynamic set of **SE**s
- The **SE**s are **not statically allocated** on a specific **LP**, they can be **migrated** to:
  - *reduce the **communication overhead***
  - *enhance the **load balancing***

Adaptive clustering: **migration of entities**

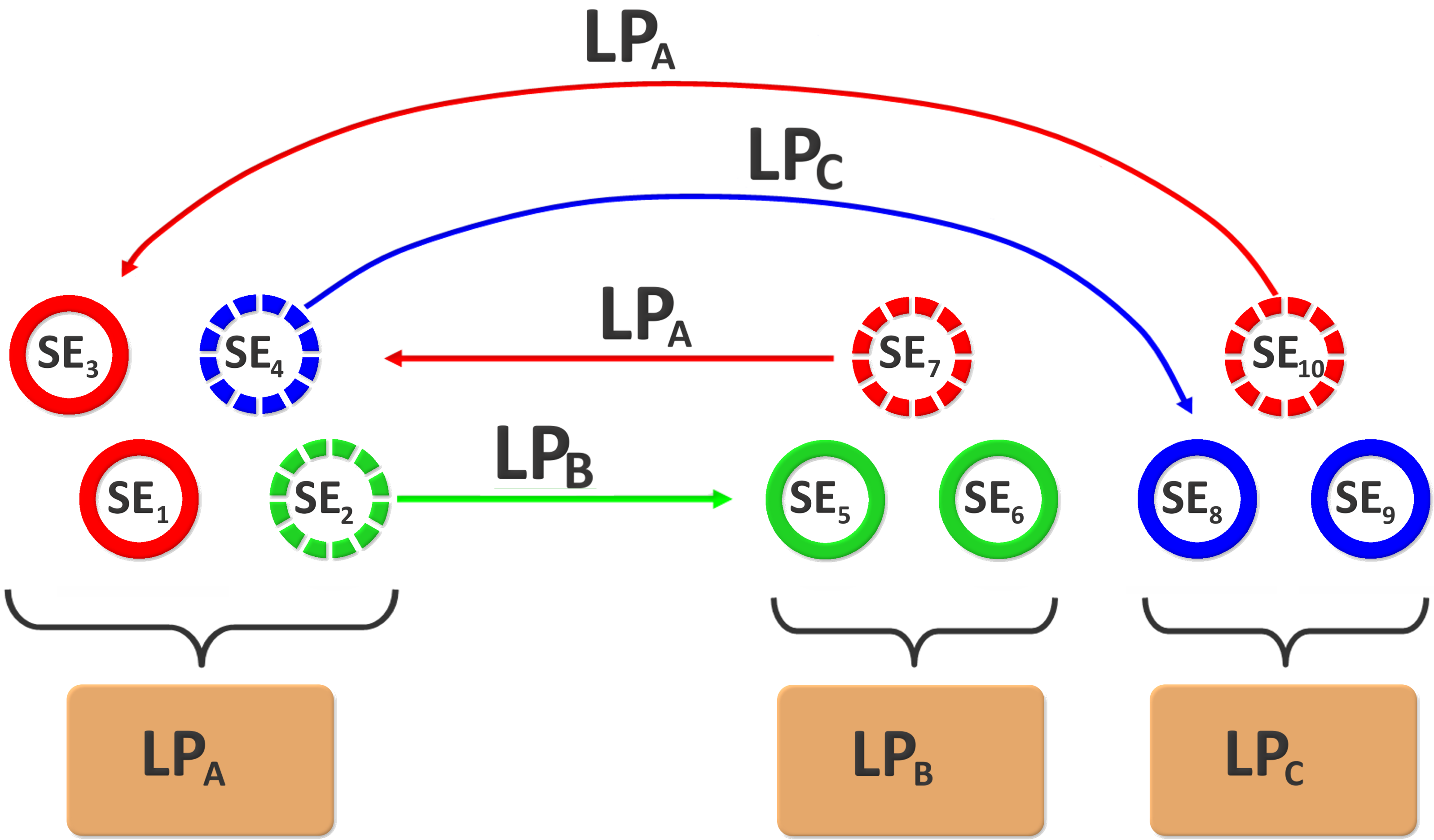
- In a parallel/distributed simulation the **communication overhead** is usually quite high
- Each **SE** will have (possibly) different **interaction patterns**
- In the simulation, it is possible to find "**interaction sets**" composed of **SE**s **interacting with high frequency**
- The main strategy is to **cluster** the **SE**s interacting with high frequency **within the same LP**
- All of this can be done **analyzing the communication pattern** of each **SE** and **migrating some of them**
- **The load balancing has to be considered!**

Adaptive clustering: **migration of entities**



In dashed lines, the **interactions** of SE_3 with other simulated entities

Adaptive clustering: **migration of entities**



In solid lines, the **migrations** that should be done to enhance the partitioning

The **ARTÌS/GAIA** simulator

simulation model

model behavior:
- state variables
- event handlers

GAIA

- high level communication APIs
- migration support
- clustering heuristics

ARTÌS

runtime services:
- synchronization
- communication
- simulation management

operating system

ARTÌS and **GAIA**, some details

- Multi-year effort for building an **efficient simulation middleware**: **A**dvanced **RTI S**ystem (**ARTÌS**)
- Used as a testbed for many research works
- The **G**eneric **A**daptive **I**nteraction **A**rchitecture (**GAIA**) framework implements the **adaptive features**:
  - ***adaptive clustering*** *for* ***overhead reduction***
  - ***dynamic load balancing*** *of communication and computation*
  - *support for* ***heterogeneous*** *execution platforms and* ***shared computing resources***
  - ***Reliable-GAIA****: support for* ***fault-tolerance*** *(work in progress)*

For details and **software download**: http://pads.cs.unibo.it

ARTÌS and **GAIA**, some details

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It is **free** for **education** and **research** purpose!

Many parts are provided with **source code** (e.g. all the simulation models)

Our goal is to **Open Source** as soon as possible the whole software stack

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Conclusions

- There is a strong demand for **scalable simulators**
- **P**arallel **A**nd **D**istributed **S**imulation (**PADS**) is the natural choice for enhancing the performance of simulations
- The diffusion of **multi-core CPU**s and **cloud computing** will deeply change the execution environment of simulations
- Current **PADS** technologies **are unable to cope with such changes**
- The simulation modeler is in charge of too may details
- We really need **smarter software**: **adaptive PADS**

Further information

Gabriele D'Angelo

Parallel and Distributed Simulation: from Many Cores to the Public Cloud

Proceedings of the International Conference on High Performance Computing and Simulation (HPCS 2011). Istanbul, Turkey, July 2011

An **extended version** of this tutorial paper is freely available at the following link:

- http://arxiv.org/abs/1105.2301

The **ARTÌS** middleware and the **GAIA** framework can be downloaded from:

- http://pads.cs.unibo.it

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A Gentle Introduction to Parallel and Distributed Simulation

Gabriele D'Angelo

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Systems simulation, 2012-2013

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