

Network Modeling and Simulation

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Chapter 1

Introduction

1.1 Introduction

1.1.1 Cells

A cell is the basic unit of all known living organism. Different cell types have different roles which then organize to form higher levels of organization. The cell is a dynamical system whose behaviour is controlled and regulated by interaction between chemical species.

1.1.2 Biochemical reactions

The interactions between molecules in a cell are known are biochemical reactions. The chemical species in a cells are in constant movement and when they collide can cause a reaction if specific reaction conditions, like the activation energy, are satisfied. The outcome of a reaction is the consumption of some species and the production of new ones to help perform the necessary activities of the cell.

1.1.2.1 Reaction kinetics

The rate of a reaction is dependent on the species involved, the number of molecules present and a basal rate or affinity. The basal rate depends on the type and number of species involved and is often constant. The rates of reaction are determined by the reaction kinetics.

1.1.2.2 Pathways

Biochemical reactions are organized in pathways, a map showing the structural relationship of molecular species and their specific cellular response. They are involved in:

- Metabolism.
- Signal transmission.
- Gene expression regulation.

They are involved in different cellular purposes like:

1.1. INTRODUCTION

- Cell growth.
- Differentiation.
- Proliferation.
- Apoptosis.

Explaining how a cellular function emerges from the molecular interactions needs a system-wide approach.

1.1.3 Systems biology

Systems biology is a new discipline that aims to understand how reactions give rise to specific cellular behaviours and a biological response. Its holistic view-point provide advantages in scientific and practical terms like:

- Drug discovery.
- Hypothesis verification.
- Disease mechanism explanation.

1.1.3.1 Challenges of system biology

The challenges of systems biology are due to the large number of possible reactions and their non-linear dynamics. In these cases the stationary and time-invariant assumptions are often violated: the species constantly evolves according to changes in the cellular environments. Moreover some molecular species are present in low copy number or population. Reaction between these cause a significant fluctuation in their population, or biological noise, which may propagate along the pathway.

1.1.3.2 Stochasticity

The stochasticity in biochemical reaction can be also due to the fact that after many non-reactive collisions between species the biological system could choose a different cellular functioning. This is called multistability: a number of separated stable equilibria points are separated by unstable equilibria. Bistability is the simplest example of multistability, with only two stable equilibria.

1.1.4 Computational tools

Computational tools play a crucial role in systems biology. Introducing a model to represent the biological system's species of interest or states and the reaction between them or state transition, knowledge of the biology can be written in a formal form, often mathematically.

1.1.4.1 Biological models

A biological model is an abstraction of the system, but it is useful to understand it. A direct way to describe a model is to write down the list of reactions between species. Modelling a reaction network by coupled reactions is simple and flexible.

1.1.4.2 Computer simulation

Given a model, a computer simulation is used to realize its temporal evolution. The dynamical interactions between species can reveal indirect implications or unexpected behaviours. A simulation based experiment is called an *in silico* experiment. If results of this experiment agree with experimental data, they can be used to provide predictions for the dynamics of the system.

1.2. DIFFERENT LEVELS OF SIMULATION

1.1.4.3 Advantages and applications of in silico experiment

With respect to traditional experiment, an in silico simulation has a number of advantages:

- It takes less time.
- It is cheaper.
- They can detect indirect and hidden implications.
- It is possible to isolate vital genes from the cell, overcoming the necessity of maintaining a vital cell.

The results of an in silico experiment are used to:

- Test hypothesis.
- Suggesting new experiments.

The predictive feature of computer simulations makes it useful to perform quantitative analysis.

1.1.5 Synthetic biology

Biological models and simulation contribute to the design and implementation of synthetic biology by providing a design focused experiment framework where models are reused as basic building blocks in a large model. This component-based model building is more effective and less error-prone than a traditional from-scratch approach. Moreover this component approach allows to reprogram cellular functions to serve for special purposes of biological research.

1.2 Different levels of simulation

To cope with the inherent multi-physics and multi-scale natures of biochemical reactions, different levels of simulation detail have been adopted to investigate their dynamical behaviour.

1.2.1 Molecular dynamics

Molecular dynamics deals with the microscopic level. In this type of simulation the structures, positions velocities and possible collisions of all molecules in the system are kept track of. Movement and reactions are governed by physical forces. A molecular dynamics simulation requires a very detailed knowledge of molecules in both time and space and requires a lot of computational power. Because of this it is used to simulate the system at the level of nanoscale of time and space.

1.2.2 Brownian dynamics

Brownian dynamics focuses on the dynamics of each individual species, skipping the molecular structure information and the weak long-range forces between species. The movement of a species is described as a random or Brownian walk among point-like structures. A reaction happens whenever the distance between two species is less than a predefined reaction radius. The time scale of a Brownian dynamics simulation is greatly improved over molecular dynamics, but it is still require too much computational power to deal with large scale models.

1.2.3 Deterministic simulation

A deterministic simulation is the highest coarse-grained approach which focuses on the macroscopic behaviour of biochemical reactions. Molecular species in the deterministic simulation approach are represented by their concentrations. The rate of change in the concentration of each species due to a reaction is directly proportional to the concentrations of the species involved in the reaction. The time evolution of a biochemical reaction network is described by a set of ordinary differential equations or ODEs. The deterministic simulation is fast, however its underlying assumption inherently oversimplifies biological reactions in which populations of molecular species are continuous variables and their changes due to single reaction firings are assumed to be negligible. The correctness of deterministic simulation is severely affected when stochasticity plays an important role in the dynamical behaviour of biochemical reactions.

1.2.4 Stochastic simulation

A stochastic simulation is a mesoscopic approach to provide a probabilistic description of the time evolution of biochemical reactions. It keeps track of a discrete count for the population, but abstracts all the detailed position and velocity information of each species. Each reaction in the network is assigned a non-negative chance to fire and to drive the system to a new state. The probability that a reaction occurs in a time interval is derived from the reaction kinetics. Each stochastic simulation step will select a reaction to fire according to its probability.

1.2.5 Problems with stochastic simulations

Although the stochastic simulation approach is faster than both a molecular dynamics or Brownian dynamics approach, it is often computational demanding for simulating large biological systems. Moreover:

- Biochemical reactions, due to their multi-scale nature, are separated by different time scales in which some fast reactions will occur at rates greater than other reactions. The dynamical behaviour of biochemical reactions, after the short fluctuation time at the beginning, will be determined by the dynamics of the slow reactions. However, most of the time the simulation samples the fast reactions to realize the dynamics which is not the expected behaviour.
- The population of some species involved in reactions may be larger than others by many orders of magnitude. This implies that the fluctuations of some species are more or less significant when involving reactions fire.
- Keeping track of large population species is less efficient, since a coarse-grained simulation method can be applied without loss of total simulation accuracy. A model can combine and mix all of these aspects making the fast reactions occur frequently and drive the system very fast into a stable state.
- Due to the stochastic behaviour in a single simulation, many simulation runs must be performed to ensure a statistical accuracy and this requires a high computational effort. These issues raise a computational challenge for developing and implementing efficient stochastic simulation methods.

1.3 Network modeling

[missing lecture 2]

1.3.1 Logic models

Recap from the previous theory lecture: what is the main issue in using logic modelling with multiple levels? The update formulae need to be defined for each level, tricky extension procedure.

1.3.2 Petri nets

Petri nets are specific networks introduced in 1960s, with the idea to describe *communication processes* (computer science field). We have two kinds of nodes:

- **places**: container of entities
 - *tokens*: entities
- **transitions**: possibility to move one or more tokens to other places

In order to model a chemical reaction, we can associate places to variables, transitions to chemical transformations and tokens to molecules.

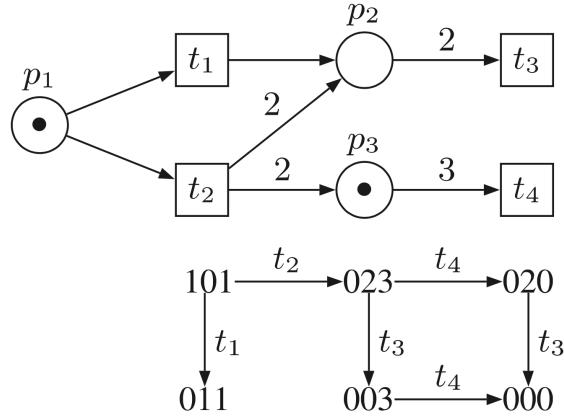


Figure 1.1: PetriNets_SimaoEtAl.pdf

Figure 1.1: in the example we have numbers inserted in places. The network will evolve according to the transitions applied. A transition can be *enabled* or not to fire. E.g. there is one token in p_1 , so we know that t_1 and t_2 are enabled. Instead, t_4 cannot be enabled, as 3 tokens are required but only one is present. t_2 is taking the token from p_1 and creating 2 tokens in p_2 and p_3 ; this allows to fire t_4 , since now p_3 has the required number of tokens.

(a) shows the initial marking before firing the enable transition t ;

1.3. NETWORK MODELING

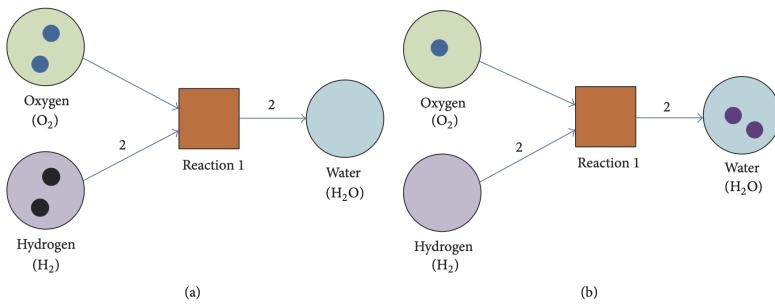


Figure 1.2: Review _ ModelingComplexBiologicalSystems.pdf

(b) shows the marking after transition labeled reaction 1 fires. Places: hydrogen, oxygen and water. We can represent the stoichiometry of the reaction through the numbers on the edges and the numbers to the tokens.

Figure 1.2

- Pros: we have no constraint on the data type, not strictly boolean values. They allow to extend the number of items which can be associated to a model.
 - Cons: there is no fixed rule for applying transitions. Furthermore, we are not encoding the reaction's complexity (all transitions are equally probable, but it is possible to weight the edges).

Having a dynamics based on the integers can be quite useful, as if we consider single chemical events we are working with discrete data. The exact stochastic algorithm works with integers. In differential equations instead we need real numbers. Also the discretization of the time step might not be a limitation, since time can be discretized in reality. The main limitation of network models is the **approximation of time**, as we are assuming that all the reactions take the same (unknown) amount of time.

By upgrading the notation we can achieve more accurate representations:

- add inhibitory and test transitions.
 - differentiate between discrete and continuous transitions.

1.3.3 Rewriting systems

1.3.3.1 P systems

Popular rewriting systems are ***P* systems**, which are also called membrane systems. They are computational environments inspired to the structure of membranes. In particular, they define a hierarchy of membranes partitioning the space in different areas - similarly to a cell. In each region we can allocate entities and apply transformation rules. The rewriting rules change the value of each letter. The pedix *in4* gives more details on the reaction. These kind of systems tend to use *non-determinism*, they try to explore the full set of possibilities.

1.3. NETWORK MODELING

1.3.3.2 MP systems

The difference with standard P system is the association of functions to each reaction. In this way we can reconstruct the complexity of the reaction, since in the model we apply all possible reaction - which will produce an amount given by the function.

1.3.4 Equation-based approach

1.3.4.1 ODE systems

Example: mass-action model $A + E \xrightleftharpoons[k_2]{k_1} A | E \xrightarrow{k_3} B + E$

1.3.5 Simulation algorithms

For simulating we need the specification of a stoichiometric matrix, a vector of integers (initial values) and a stochastic rate. **Exact simulation algorithms** are computationally intensive, but provide the most accurate solution. Stepwise, we will try to define faster strategies with the aim of compromising accurate dynamics and feasible solutions. It is also possible to rely on a mixture of technologies to focus on different results. If the well-mixed assumption is not fulfilled:

- partition the compartment in sub-compartments → approximation
- use more sophisticated algorithms

The *stoichiometric matrix* tells us how the system evolves if one of the two functions is applied, but it is not enough for computing a simulation. There can be many reactions that arrive to the same definition of stoichiometric matrix. If we want to compute a dynamics we need to develop a series of states; at each step we require two ingredients:

- τ : tells how much later the system will evolve to another state
- μ : choose the reaction by considering the probability of execution of each reaction at the step

1.3.5.1 Reaction propensity

The reaction propensity is a function needed for the derivation of probability. The higher the propensity, the higher will be the strength of the reaction. Naturally, we will have a higher probability when a higher propensity is observed, but the two quantities are something different. The propensity is a property of the reaction, probability is a property of a reaction in the system (we need to take into account also other reactions) Instead of performing an in depth analysis of probability, we will choose a stochastic approach. It is only necessary to compute one evolution of the system per time.

Chapter 2

Stochastic simulation of biochemical reaction systems

2.1 Introduction

Biochemical reaction network can be modelled through stochastic chemical kinetics. In this type of models the discreteness in population of species and the randomness of reactions are treated as an intrinsic part. The dynamical behaviour is described by the chemical master equation or CME.

2.2 Stochastic chemical kinetics

2.2.1 Rewriting biochemical reactions

Biochemical reactions are the building blocks to model biological systems. They provide a unifying notation with sufficient level of details to represent complex biological processes. Biochemical reactions decorated with reaction kinetics can be simulated by a simulation algorithm to generate a realization of their dynamics. Chemical species in a biological system move around and gain kinetic energy. Upon collisions with other species, they undergo reactions to modify and transform into different species.

2.2.1.1 Representing molecular reactions

Molecular reactions can be classified between elementary reactions and non-elementary ones. The former require one step to complete, while the latter require a higher order reactions or a multi-step one.

2.2.1.1.1 Some elementary reactions

2.2.1.1.1 Unimolecular reaction An unimolecular reaction involves the transformation of one species into another. It can be represented as:



2.2. STOCHASTIC CHEMICAL KINETICS

2.2.1.1.1.2 Degradation The degradation of a species is a special type of an unimolecular reaction in which a species is degraded:



Where the symbol \emptyset represents a species that is not considered in the model, probably because it is large and does not change over time.

2.2.1.1.1.3 Synthesis The synthesis of a species is another type of unimolecular reaction in which a species is synthesised:



This reaction is used to model the effects of the outside environment on system dynamics.

2.2.1.1.1.4 Bimolecular reaction An example of a bimolecular reaction is an association reaction, in which a molecule can associate with another to produce a complex:



Often this process is reversible and the inverse dissociation reaction can take place:

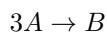


2.2.1.1.1.5 Dimerization The dimerization is a special bimolecular reaction in which two molecules of the same species are consumed to produce another species:

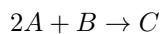


2.2.1.1.2 Some non-elementary reactions

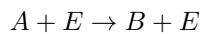
2.2.1.1.2.1 Termolecular reaction The thermolecular reaction is used to represent the polymerization of three molecules into another species. The original molecules can be of the same species:



Or of two different species:



2.2.1.1.2.2 Enzymatic reaction Another multi-step reaction is an enzymatic reaction, where the enzyme W that catalyses the rate of conversion is kept the same:



2.2.1.2 Equation-based methods

The previous way to represent reactions does not give insight on the function of the equation. To shine light on this aspect equation-based methods need to be applied, like ordinary differential equation systems. In these the derivative with respect to time is specified for any of the variables in term of a function of the state. It can be noted how the stochastic simulation approach can be approximated by a deterministic one.

2.2.1.3 Creating a formal mathematical description of a biological system

To write a mathematical description of a biological system there is a need to:

1. Choose the biochemical reactions' representation.
2. Choose the type of variable to describe the state of the system.
3. Specify the likelihood of execution for each reaction.

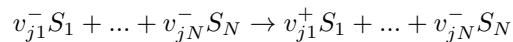
A reaction will be faster when there is a huge amount of reactants. This is because in term of probability: the more a species is present, the more it is likely to interact and for the reaction is to happen. This is true only when the assumption of that there is a well-mixed reaction volume is made. This assumption entails that the distribution of molecules is uniform. Moreover, in order to approximate a complex system the main compartments can be partitioned in smaller sets where a discretization procedure can be applied. Therefore in this case Petri nets are a suitable representation for these kind of systems.

2.2.1.4 Well-mixed reaction volume

A well-mixed reaction volume is a reaction volume in which all the molecular species are homogeneously distributed and spatially indistinguishable. This is legitimate as non-reactive conditions are much more frequent than reactive ones. The biochemical reaction system with well-mixed volume thus satisfies the spatial homogeneity condition, where spatial distribution of molecular species can be ignored. Chemical species under the well-mixed assumption at a thermal equilibrium are uniformly distributed in the volume V and their velocities are thermally randomized according to the Maxwell-Boltzmann distribution.

2.2.1.5 Formal representation

The state of a spatially homogeneous biological system is determined by the population of each species, while the position and velocity of each individual molecule are ignored. Let $X_i(t)$ be the population of species S_i at a particular time t . The N-vector $X(t) = (X_1(t), \dots, X_N(t))$, which determines the population of each species, constitutes the system state at the time t . Chemical species interact through M reactions R_1, \dots, R_M . A general reaction R_j has a general scheme:



Where:

- Species on the left side are reactants.
- Species on the right side are products.
- The non-negative integers v_{ji}^- and v_{ji}^+ are the stoichiometric coefficients which denote the number of molecules of a reactant that

2.2. STOCHASTIC CHEMICAL KINETICS

are consumed and the number of molecules of a product that are produced.

A reactant species that affects the speed of a reaction but is not consumed by it is called a catalyst. The sum of stoichiometric coefficients of reactants of a reaction R_j is called reaction order. For each reaction R_j , the net change in the population of species S_i involved in the reaction is equal to $v_{ji}^+ - v_{ji}^-$, which can be positive, negative or zero.

2.2.1.6 Stoichiometric matrix

The net changes by all reactions are described by a stoichiometry matrix \vec{v} of size MN . The j th row \vec{v}_j of the stoichiometry matrix expresses the changes caused by reaction R_j and it is called the state change vector. Different system can lead to the same stoichiometric matrix. To describe a reaction two matrices are required:

- V^+ provides the products.
- V^- provides the reactants.

$$V^- = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}, V^+ = \begin{bmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 2 & 0 & 0 \end{bmatrix}, V = \begin{bmatrix} 1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} V = V^+ + V^-$$

Suppose that at a time t the state, or number of molecules in that given moment is $X(t)$. It is further assumed that the next reaction scheduled to fire at the next time $t + \tau$ is R_μ , which move the system accordingly to a new state $X(t + \tau)$. \vec{x} is a simple notation to represent $X(t)$. Two important assumptions are made for the transition from state $X(t)$ to state $X(t + \tau)$:

- No changes occur in the system state during the time interval $[t, t + \tau]$, before the next reaction fires.
- The reaction occurs instantly after it is initiated.

These are called the Markov property. So the evolution of the system in a time step will be:

$$X(t + \tau) = X(t) + v_\mu$$

2.2.1.7 Summary

While specifying in computational terms the biological system of interest, the structure of at least one compartment has to be described, where it is assumed to find a chemical volume in which there are some entities that interact with each other. The he well-mixed volume preliminary assumption is enforced, meaning that all the actors are present with equal availability in all the parts of the volume. For each compartment, the entities or how many molecules are available, and the reactions that provide the rules for transforming the chemicals in others along the time have to be specified. All these structures of reactions can be defined in mathematical terms using matrices: the number of columns is equal to the number of variables, while the number of rows is equal to the number of reactions and the stoichiometric coefficient of the transformation from reactant to products is specified.

2.2.2 Reaction propensity

Each reaction in stochastic chemical kinetics is considered as a *stochastic process* where each of its occurrence is a random event with an assigned probability distribution. It is impossible to predict the progress of reactions deterministically, but only stochastically with a probability. The propensity of a reaction is a formula that is computed on a state of a system. Through the reaction propensity the probability of execution of a reaction will be hinted.

2.2.2.1 Definition

The propensity a_j of a reaction R_j is defined such that $a_j(x)dt$ is probability that a reaction R_j fires in the next infinitesimal time interval $[t, t + dt]$, given the state $X(t) = \vec{x}$ at time t . In a chemical setting, the probability of execution of one reaction will be proportional to the viability of the reactant.

2.2.2.2 Value of the propensity

The propensity $a_j(X(T))$ is a function of the state $X(t)$. The fact that a_j of a reaction depends on time t happens implicitly through the Marcokian assumptions. At a particular time t , the value of the propensity $a_j(X(T))$ is a deterministic quantity. The propensity value of a reaction in state $X(t)$ is often used as a measure of how fast the reaction proceeds to move to a new state. Let $\mathcal{P}\{R_j \text{ fires} \in [t, t + dt]\}$ be the probability that reaction R_j fires in the time interval. Given the state $X(t) = \vec{x}$ at time t , then:

$$\mathcal{P}\{R_j \text{ fires} \in [t, t + dt]\} = a_j(\vec{x})dt + o(dt)$$

Where $o(dt)$ expresses that it asymptotically approaches zero faster than dt : $\lim_{dt \rightarrow 0} \frac{o(dt)}{dt} = 0$. In other words the probability that there are more than one firing of R_j in the time step i in order of $o(dt)$ and so it is negligible. The propensity of a reaction is an intrinsic property of the reaction and is linked to the phenomenon that the reaction is going to represent. The probability will depend on the propensity of the reaction and the other reactions that are competing for the same reactant. The propensity is not affected by the products.

$$a_1(0) = c_1 h_1(x(0))$$

$$h_2(x(0)) = \begin{pmatrix} 100 \\ 1 \end{pmatrix} \begin{pmatrix} 50 \\ 1 \end{pmatrix} \begin{pmatrix} 30 \\ 0 \end{pmatrix}$$

$$x(0 + \tau) = x(0) + V_1 = [99 \quad 51 \quad 30]$$

$$x(0) = [100 \quad 50 \quad 30]$$

Since the combination is being computed a^2 will not be taken into account as in the canonical law of mass action.

2.2. STOCHASTIC CHEMICAL KINETICS

2.2.2.3 Mass action propensity

A precise formula for the propensity function a_j is dependent on the kinetics and a specific assumption about how the reaction occurs physically. This is referred as the fundamental premise of the stochastic chemical kinetics. For the standard mass action kinetics, the propensity a_j of reaction R_j is proportional to a stochastic reaction rate c_j and the number of its reactants. So given current state $X(t)$ at time t :

$$a_j(X(t)) = c_j h_j(X(t))$$

Where c_j is the stochastic reaction rate and $h_j(X(t))$ counts the number of distinct combination of reactants:

$$h_j(X(t)) = \prod_i \binom{X_i(t)}{v_{ji}^-} = \prod_i \frac{X_i(t)!}{v_{ij}^0!(X_i(t) - v_{ij}^-)!}$$

In the case of a synthesis reaction, where the stoichiometric coefficient of its reactants is 0 is set to $h_j(X(t)) = 1$.

2.2.2.3.1 The stochastic rate The stochastic rate c_j denotes the average probability per unit time that a particular combination of reactant molecules of reaction R_j reacts in the volume V and depends on the reaction type. In the case of a unimolecular reaction is independent of the volume size, while in the case of a bimolecular one it will be inversely proportional of it. The rate is constant provided that:

- The volume V is constant.
- The volume is thermally homogeneous.
- The volume is well-mixed.

2.2.2.4 Reaction propensity for reactions R_j with mass action kinetics

From now X_i will be used in place of $X_i(t)$, when t is irrelevant or clear from the context. Some reaction will be described by mass action kinetics by:

- Synthesis reaction ($\emptyset \rightarrow$ products): the number of combinations $h_j = 1$ and propensity $a_j = c_j$
- Unimolecular reaction ($S_i \rightarrow$ products): the number of combinations $h_j = X_i$ and propensity $a_j = c_j X_i$.
- Bimolecular reaction ($S_i + S_k \rightarrow$ products): the number of combinations $h_j = X_i X_k$ and propensity $a_j = c_j X_i X_k$.
- Dimerization reaction ($2S_i \rightarrow$ products): the number of combinations $h_j = \frac{1}{2} X_i (X_i - 1)$ and propensity $a_j = \frac{1}{2} c_j X_i (X_i - 1)$.
- Polymerization reaction ($3S_i \rightarrow$ products): the number of combinations $h_j = 16 X_i (X_i - 1)(X_i - 2)$ and propensity $a_j = 16 c_j X_i (X_i - 1)(X_i - 2)$.
- Termolecular reaction ($2S_i + S_k \rightarrow$ products): the number of combinations $h_j = \frac{1}{2} X_i (X_i - 1) X_k$ and propensity $a_j = \frac{1}{2} c_j X_i (X_i - 1) X_k$.

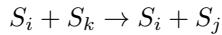
2.2. STOCHASTIC CHEMICAL KINETICS

2.2.2.5 Complex reaction kinetics

Complex reaction kinetics can be used. The propensity a_j will show a complicated, non-linear dependence on the chemical species and may contain more than one rate constant.

2.2.2.5.1 Michaelis-Menten kinetics

The Michaelis-Menten kinetics is used to approximate the mechanism of enzymatic reaction. Consider an enzymatic reaction R_j with form:



Where:

- S_k is the substrate.
- S_i is the enzyme.

The reaction propensity will be defined as:

$$a_j = \frac{V_{\max}}{K_M + x_k} X_i X_k$$

Where:

- V_{\max} is the maximum rate such that the substrate S_k is saturated.
- K_m or Michaelis constant is the substrate concentration at which the reaction rate is half of V_{\max} .

2.2.3 Chemical Master Equation

The chemical master equation or CME is the theoretical approach allowing to derive the complete set of probabilities of all the possible states of the system. Suppose that the biochemical reaction system starts with an initial state $X(t_0) = \vec{x}_0$. Let $t > t_0$ and the system at state $X(t) = \vec{x}$, The purpose of the stochastic chemical kinetics is to infer the probability:

$$\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}$$

2.2.3.1 Grand probability function

The probability function or grand probability:

$$\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_o\}$$

Is the probability that the system state is $X(t) = \vec{x}$ at time t , given the initial state $X(t_0) = \vec{x}_0$ at time t_0 . It is called so because it gives the probabilities of all reachable states of the system at time t given the initial state. Knowing it all the statistical properties can be computed for every species at any time.

2.2.3.2 Deriving the chemical master equation

To derive the time evolution of the grand probability, consider an infinitesimal time interval $[t, t+dt]$ so that there is at most one reaction in that interval. Suppose that at time $t+dt$ the system state is $X(t+dt) = \vec{x}$. There are two cases in order to reach the state \vec{x} in the time-step given the current time:

2.2. STOCHASTIC CHEMICAL KINETICS

- At time t the state is $X(t) = \vec{x} - \vec{v}_j$ and reaction R_j fires in the next time step leading to $X(t + dt) = \vec{x}$.
- At time t the state is already $X(t) = \vec{x}$ and no reaction fires in the time step.

Then the grand probability can be written as:

$$\begin{aligned}\mathbb{P}\{\vec{x}, t + dt | \vec{x}_0, t_0\} &= \sum_{j=1}^M \mathbb{P}\{R_j \text{ fires } \in [t, t + dt]\} \mathbb{P}\{\vec{x} - \vec{v}_j, t | \vec{x}_0, t_0\} + \\ &\quad + \mathbb{P}\{\text{No reaction fires } \in [t, t + dt]\} \mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}\end{aligned}$$

Note that when the state vector $\vec{x} - \vec{v}$ gives negative populations, the probability $\mathbb{P}\{\vec{x} - \vec{v}_j, t | \vec{x}_0, t_0\}$ is zero because the populations of species must be positive. Now, the probability that no reaction fires in the time-step can be computed as:

$$\begin{aligned}\mathbb{P}\{\text{No reaction fires } \in [t, t + dt]\} &= \prod_{j=1}^M (1 - \mathbb{P}\{R_j \text{ fires } \in [t, t + dt]\}) = \\ &= \prod_{j=1}^M (1 - a_j(\vec{x})dt + o(dt)) = \\ &= 1 - \prod_{j=1}^M a_j(\vec{x})dt + o(dt)\end{aligned}$$

Then substituting the definition of the probability of a reaction firing and the probability of a reaction non firing just computed into the grand probability function:

$$\begin{aligned}\mathbb{P}\{\vec{x}, t + dt | \vec{x}_0, t_0\} &= \sum_{j=1}^M \mathbb{P}\{\vec{x} - \vec{v}_j, t | \vec{x}_0, t_0\} (a_j(\vec{x} - \vec{v}_j)dt + o(dt)) + \\ &\quad + \mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\} \left(1 - \sum_{j=1}^M a_j(\vec{x})dt + o(dt) \right)\end{aligned}$$

Subtracting $\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}$ from both sides, dividing by dt and considering the limit $dt \rightarrow 0$, the chemical master equation is obtained:

$$\frac{\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}}{dt} = \sum_{j=1}^M (a_j(\vec{x} - \vec{v}_j) \mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\} - \mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\} \sum_{j=1}^M a_j(\vec{x}))$$

The chemical master equation is a collection of differential equations in which each of them represents the probability of each possible state of the system at time t . It provides a complete description of the time evolution of the grand probability:

$$\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}$$

2.3. STOCHASTIC SIMULATION

2.2.3.3 Limitations of the chemical master equation

The chemical master equation allows to compute the probabilities of all possible states at any time, however directly solving it require a lot of computational challenges:

- An analytical or numerical approach to solve CME in general is non-trivial to find.
- There is a huge number of differential equations: a^N , where N is the number of species and a is the values of the population of each species.

So it can be seen how the number of differential equations increases exponentially, making the state space explode in dimension, preventing direct approaches in solving CMEs.

2.3 Stochastic simulation

When applying the CME, all the possible state of the system are explored. With a stochastic simulation only one possible trajectory of the system are computed (to obtain the total description many simulations have to be run). The stochastic simulation works because only an idea of the most probable conditions of the system is needed. A stochastic simulation is faster than a real experiment and it can be run on a personal computer (also thousands of simulations can be performed). One of the crucial points of a stochastic simulation is that there is a need to be able to sample from this probability distribution function given the fact that the computer has few ways of generating something that is stochastic. The easiest way to do so is through a random number generator.

2.3.1 Probability density function

Stochastic simulations are an alternative approach to solve CME by producing possible realization of the grand probability function. It only explores possible states in the state space each time, so they can handle the biochemical reactions with very high-dimensional state space. The mathematical basis of a stochastic simulation is the reaction probability density function pdf:

$$p(\tau, \mu | \vec{x}, t)$$

Which is defined such that $p(\tau, \mu | \vec{x}, t)d\tau$ is the probability that a reaction R_μ fires in the next infinitesimal time interval $[t + \tau, t + \tau + d\tau]$, given the state $X(t) = \vec{x}$ at time t . The pdf $p(\tau, \mu | \vec{x}, t)$ is a joint distribution of two variables showing the index μ of the reaction firing R_μ at time τ of the firing respectively, knowing that the system is at state $X(t)$ at time t . The reaction index μ will vary from $1 \leq \mu \leq M$, while the next time τ will vary from $0 \leq \tau \leq \infty$.

2.3.1.1 Computing the probability density function

The probability $p(\tau, \mu | \vec{x}, t)dt$ can be computed as the product of:

- The probability that no reaction fires in the time interval $[t, t + \tau[$.
- The probability that a reaction R_μ fires in the next infinitesimal interval $[t + \tau, t + \tau + d\tau[$.

Let:

2.3. STOCHASTIC SIMULATION

- $\mathbb{P}\{\text{No reaction fires } \in [t, t + \tau]\}$ be the probability that no reaction fires in the time interval $[t, t + \tau]$.
- $\mathbb{P}\{R_\mu \text{ fires } \in [t + \tau, t + \tau + d\tau]\}$ be the probability that reaction R_μ fires in the next infinitesimal time interval $[t + \tau, t + \tau + d\tau]$.

Then:

$$p(\tau, \mu | \vec{x}, t) d\tau = \mathbb{P}\{\text{No reaction fires } \in [t, t + \tau]\} \mathbb{P}\{R_\mu \text{ fires } \in [t + \tau, t + \tau + d\tau]\}$$

To compute the probability that no reaction fires the time interval is divided into k non overlapping sub interval of length $\epsilon = \frac{k}{\tau}$. The probability that no reaction fires in the i -th interval $[t + (i - 1)\epsilon, t + i\epsilon] \forall i = 1, \dots, k$ is:

$$\mathbb{P}\{\text{No reaction fires } \in [t + (i - 1)\epsilon, t + i\epsilon]\} = 1 - \sum_{j=1}^M a_j(\vec{x})\epsilon + o(\epsilon)$$

Hence the probability that no reaction fires in $[t, t + \tau]$ is the product of the probabilities that no reaction fires in k non-overlapping intervals:

$$\begin{aligned} \mathbb{P}\{\text{No reaction fires } \in [t, t + \tau]\} &= \prod_{i=1}^k \mathbb{P}\{\text{No reaction fires } \in [t + (i - 1)\epsilon, t + i\epsilon]\} = \\ &= \prod_{i=1}^k \left(1 - \sum_{j=1}^M a_j(\vec{x})\epsilon + o(\epsilon) \right) = \\ &= \left(1 - \sum_{j=1}^M a_j(\vec{x})\epsilon + o(\epsilon) \right)^k = \\ &= (1 - a_0(\vec{x})\epsilon + o(\epsilon))^k \end{aligned}$$

Where $a_0(\vec{x})$ is the total propensity defined as:

$$a_0(\vec{x}) = \sum_{j=1}^M a_j(\vec{x})$$

In the limit case where $k \rightarrow \infty$:

$$\begin{aligned} \mathbb{P}\{\text{No reaction fires } \in [t, t + \tau]\} &= \lim_{k \rightarrow \infty} (1 - a_0(\vec{x})\epsilon + o(\epsilon))^k = &= \lim_{k \rightarrow \infty} \left(1 - \frac{a_0(\vec{x})k\epsilon + ko(\epsilon)}{k} \right)^k = \\ &= \lim_{k \rightarrow \infty} \left(1 - \frac{a_0(\vec{x})\tau + \tau(\frac{o(\epsilon)}{\epsilon})}{k} \right)^k = \\ &= e^{-a_0(\vec{x})\tau} \end{aligned}$$

The last step is true because:

2.3. STOCHASTIC SIMULATION

- $\frac{o(\epsilon)}{\epsilon} \rightarrow 0$ when $k \rightarrow \infty$.
- $\lim_{k \rightarrow \infty} \left(1 - \frac{a_0(\vec{x})\tau}{k}\right)^k = e^{-a_0(\vec{x})\tau}$.

The probability that a reaction fires, following the definition of the reaction propensity is computed by:

$$\mathbb{P}\{R_\mu \text{ fires } \in [t + \tau, t + \tau + d\tau]\} = a_\mu(\vec{x})d\tau + o(d\tau)$$

Now plugging everything in the definition of the probability:

$$p(\tau, \mu | \vec{x}, t) d\tau = e^{-a_0(\vec{x})\tau} (a_\mu(\vec{x})d\tau + o(d\tau))$$

Dividing both sides by $d\tau$ and taking the limit $d\tau \rightarrow \infty$ and remembering that $\frac{o(d\tau)}{d\tau} \rightarrow 0$, the pdf will have the formula:

$$p(\tau, \mu | \vec{x}, t) = a_\mu(\vec{x})e^{-a_0(\vec{x})\tau}$$

Which is the joint probability density function of the next reaction index μ and the next firing time τ over their domains. This can be verified as:

$$\int_0^\infty d\tau \sum_{\mu=1}^M p(\tau, \mu | \vec{x}, t) = \sum_{\mu=1}^M a_\mu(\vec{x}) \int_0^\infty d\tau e^{-a_0(\vec{x})\tau} = 1$$

The pdf depends on the propensities of all reaction as well as on all species.

2.3.2 Stochastic simulation algorithm

$$p(\tau, \mu | \vec{x}, t) = a_\mu(\vec{x})e^{-a_0(\vec{x})\tau}$$

Is the framework for a class of exact Monte Carlo simulation techniques originating from the stochastic simulation algorithm or SSA. It is a discrete event simulation: the state is updated by a random selected reaction R_μ and a discrete time τ sampled from the pdf. It exactly generates μ of the reaction and the firing time τ without introducing approximation in sampling the pdf. A general sketch of the SSA procedure is outlined in algorithm 1.

Algorithm 1: Stochastic simulation algorithm (SSA) - General Sketch()

- 1 **Input:** a biochemical reaction network of M reactions in which each reaction R_j , $j = 1, \dots, M$ is accompanied with the state change vector \vec{v}_j and the propensity a_j , the initial state \vec{x}_0 at time 0 and the simulation ending time T_{\max}
 - 2 **Output:** a trajectory of the biochemical reaction network which is a collection of states $X(t)$ for time $0 \leq t \leq T_{\max}$
 - 3 $t = 0$
 - 4 $\vec{X} = \vec{x}_0$
 - 5 **while** $t < T_{\max}$ **do**
 - 6 $a_0 = 0$
 - 7 **foreach** R_j **do**
 - 8 compute a_j
 - 9 $a_0 = a_0 + a_j$
 - 10 sample reaction R_μ and firing time τ from $p(\tau, \mu, | \vec{x}, t)$
 - 11 $\vec{X} = \vec{X} + \vec{v}_\mu$
 - 12 $t = t + \tau$
-

2.4. SIMULATION OUTPUT ANALYSIS

For each iteration in the while loop the algorithm computes the propensity a_j for each reaction and the total propensity. The next reaction R_μ and its firing time τ are sampled from the pdf, a step that may need the generation of randomly distributed random numbers. The state is updated and the time is advanced to $t = t + \tau$. The loop is repeated until $t > T_{\max}$. The propensities are updated at each iteration to reflect changes in the populations of species caused by reaction firings, but this can be skipped by employing an appropriate sampling technique. The result of the algorithm is a trajectory, that shows the evolution of the biological system over time. This is a collection of states $X(t)$ that denotes the state of the system at any time $0 \leq t \leq T_{\max}$. It should be emphasized that because SSA is a discrete event simulation algorithm, the state changes only at discrete time instants when reactions fire. The state between two reaction firings is a constant.

2.4 Simulation output analysis

The trajectory obtained from a SSA run represents a possible realization of the grand probability $\mathbb{P}\{\vec{x}, t | \vec{x}_0, t_0\}$. Many independent run started with the same initial conditions are needed to have a reasonable statistical estimation.

2.4.1 Confidence interval estimation

Let K be the number of simulation and \vec{X}^r , with $r = 1, \dots, K$ be a realization of the state \vec{X} obtained at time t by the r -th independent run of SSA. The statistical properties can be derived from the ensemble of the trajectories, that are ensured to approach the exact solution of the CME as $K \rightarrow \infty$. Let $\langle \vec{X} \rangle$ be the sample mean and s^2 the unbiased variance. They are computed as:

$$\langle \vec{X} \rangle = \frac{\sum_{r=1}^K \vec{X}^r}{K} \quad s^2 = \frac{\sum_{r=1}^K (\vec{X}^r - \langle \vec{X} \rangle)^2}{K-1}$$

The sample mean and variance will approach the mean and variance of the random variable \vec{X} when K tends to infinity:

$$\mathbb{E}[\vec{X}] = \lim_{K \rightarrow \infty} \langle \vec{X} \rangle \quad \text{Var}[\vec{X}] = \lim_{K \rightarrow \infty} s^2$$

The convergence of the estimation is measured by the size of the confidence interval as the number of simulation runs is limited:

$$d = \frac{zs}{\sqrt{K}}$$

Where z is a confidence interval, denoting the percentage of the range of estimated values expected to include the true value. When it is fixed, the probability that the mean lies in the interval $[\langle \vec{X} \rangle - d, \langle \vec{X} \rangle + d]$ is $2\phi(z) - 1$, where ϕ is the cumulative distribution function or cdf of the normal distribution $\text{norm}(0, 1)$. The required number of simulation runs to achieve a specified confidence interval size can be computed:

$$K = \frac{z^2 s^2}{d^2}$$

K depends reciprocally on the square of the confidence interval size d and on the sample variance s^2 , which is unknown. One approach to circumvent this problem is to perform first a small number of trial runs to estimate s_{trial}^2 , which is applied to compute the number of simulation runs necessary:

$$K = \frac{z^2 s_{trial}^2}{d^2}$$

2.4.2 Probability distribution equation

Bistability is a form of multistability where two separated stable equilibrium points are separated by an unstable equilibrium, the average population of species might not provide enough information for their dynamical behaviour. The probability distribution must be used to quantitatively analyse the simulation results. The probability distribution can be estimated by using the histogram or empirical distribution function of the samples. It is ensured to converge to the exact probability distribution given a large number of simulation runs K . The following assumes X to be a scalar value, but it can be easily extended to the general case. To compute the histogram the state X at time t obtained by K simulation runs of SSA is supposed to be bounded into an interval $[X_{\min}, X_{\max}]$, chosen arbitrarily. Then the interval is divided into B bins, such that the i -th bin I_i is defined as the subinterval:

$$\left[X_{\min} + \frac{(i-1)L}{B}, X_{\min} + \frac{iL}{B} \right]$$

Where $L = X_{\max} - X_{\min}$. The histogram h_X of state X is then defined as:

$$h_X(I_i) = \frac{B}{KL} \sum_{r=1}^K \mathcal{X}(X^r, I_i)$$

Where X^r is the realization of X by the r -th simulation and $\mathcal{X}(X^r, I_i)$ is defined as:

$$\mathcal{X}(X^r, I_i) = \begin{cases} 1 & X^r \in I_i \\ 0 & \text{otherwise} \end{cases}$$

The histogram therefore gives the average probability of X in interval I_i . Let now p_X be the probability distribution of state X . When $K \rightarrow \infty$ and $B \rightarrow \infty$, I_i reduces to a point and h_X converges to p_X at this point. Formally:

$$p_X = \lim_{K,B \rightarrow \infty} h_X$$

Chapter 3

Implementation of the Stochastic Simulation Algorithms

3.1 Introduction

3.1.1 Non-deterministic vs stochastic

Working under the assumption of using the same model and parameters:

- A deterministic system does not show randomness and the same result is always obtained.
- A non-deterministic system shows some degree of uncertainty: different runs have different results.

3.1.1.1 Exact stochastic simulation

In an exact stochastic simulation, if some hypotheses are satisfied the system will behave like the biological one. Although the probability function could be computed, this does not make the method deterministic: uncertainty is intrinsic in the model. Theoretically there is no insight on the execution of the reactions in a stochastic setting, but a high level of accuracy can be reached thanks to the probability function.

3.1.2 Advantages of a non-deterministic approach

The reasoning behind the employment of a non-deterministic approach lies in the fact that to model a biological system there is a need to compromise between time and complexity. In non-deterministic polynomial time algorithms don't have an efficient solution, but it seems possible to find it. A non-deterministic setting allows us to understand whether an algorithm can be solved in polynomial time by step-wise guessing.

3.1.3 Categories of the exact simulation algorithms

A summary of the main exact stochastic simulation algorithms is reported in figure 3.1.

3.2. DIRECT METHOD

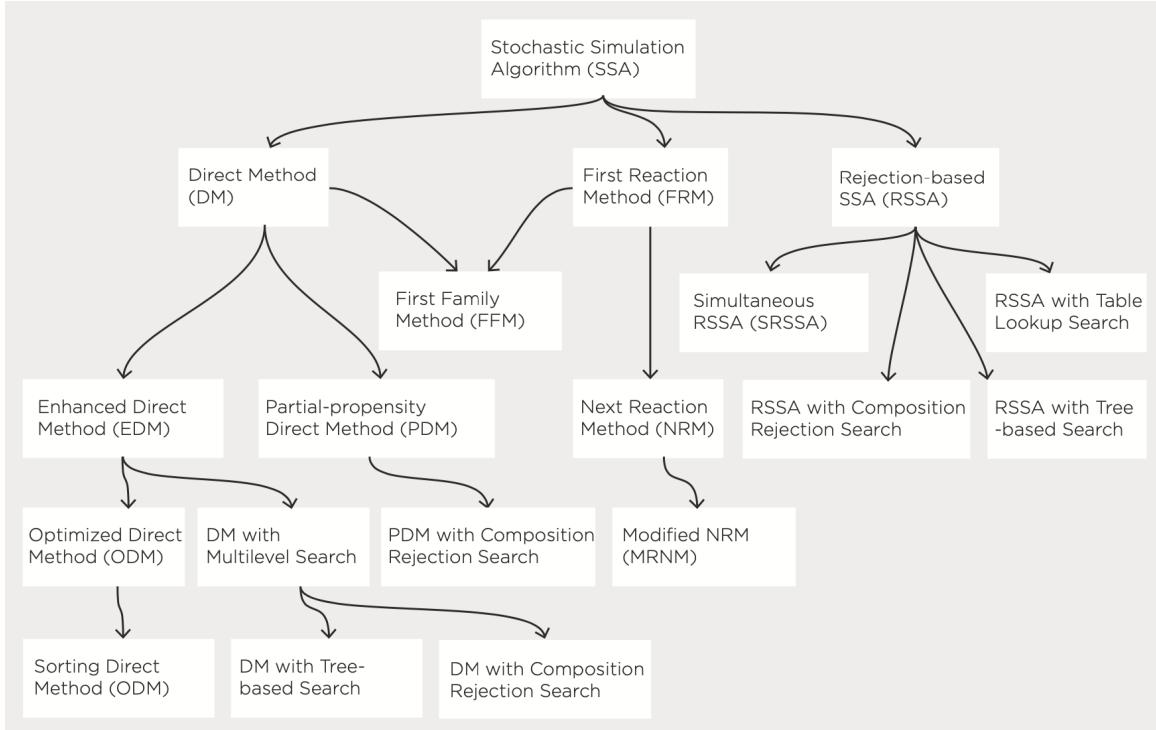


Figure 3.1: Main stochastic simulation algorithm.

3.2 Direct method

Gillespie's direct method defines a couple of formulae able to understand how the system will execute in terms of time τ and reactions μ . Since each time step is infinitesimal each reaction occurs and ends exactly at time τ , hence there cannot be multiple reactions firing simultaneously. Let a_0 be the sum of all propensities in the system, then the algorithm works as follow:

1. Sample one random number from the distribution $a_0 = \sum_{j=1}^M a_j \rightarrow V_1 = U(0, 1)$.
2. Scale it to the maximum $V_1 \cdot a_0 = U(0, a_0)$.
3. See where this number will point over the different propensities (Figure 3.2).

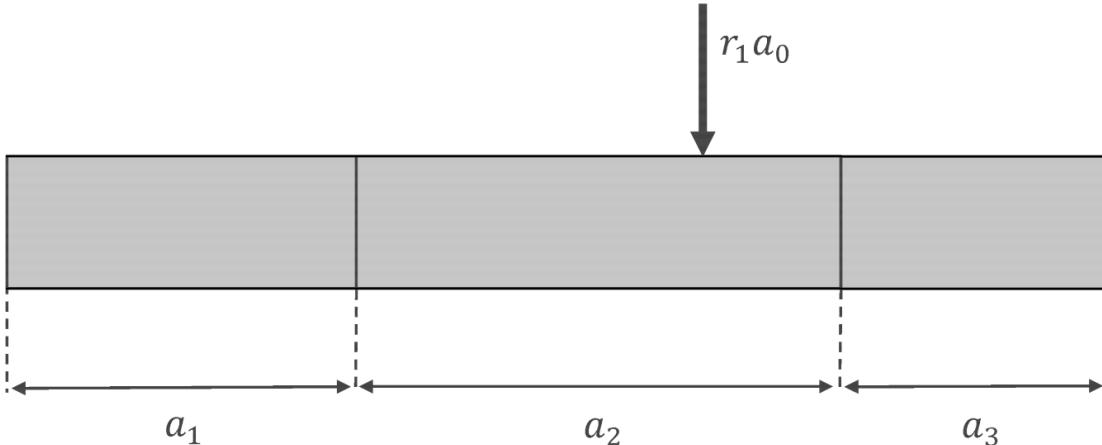


Figure 3.2: Boundaries on the propensities.

4. Generate another random number $V_2 = U(0, 1)$
5. $\tau \sim Exp(a_0)$
6. $\tau = \frac{1}{a_0} \ln(\frac{1}{V_2})$.

3.2.1 Mathematical discussion

Gillespie's direct method is used to sample the pdf $p(\tau, \mu | \vec{x}, t)$. The direct method partitions the joint probability density function into the product of two one-variable probability functions, one for τ and one for μ that can be sampled independently. The pdf can be factorized by the chain rule of probability as:

$$p(\tau, \mu | \vec{x}, t) = p_1(\tau | \vec{x}, t) p_2(\mu | \vec{x}, t)$$

Where:

- p_1 is the probability density function of the firing time τ .
- p_2 is the probability density function of the reaction with index μ that fires at $t + \tau$.

So that $p_1(\tau | \vec{x}, t) d\tau$ is the probability that a reaction will fire in the next time interval $[t + \tau, t + \tau + d\tau]$. This marginal probability is obtained by summing the probability $p(\tau, \mu | \vec{x}, t) d\tau$ over the domain of all possible values of reaction index μ :

$$p(\tau | \vec{x}, t) = \sum_{\mu=1}^M p(\tau, \mu | \vec{x}, t) = \sum_{\mu=1}^M a_\mu e^{a_0 \tau} = a_0 e^{-a_0 \tau}$$

Where a_0 is the total propensity. Plugging this and recalling the formula of the joint pdf:

$$p_2(\mu | \tau, \vec{x}, t) = \frac{p(\tau, \mu | \vec{x}, t)}{p_1(\tau | \vec{x}, t)} = \frac{a_\mu}{a_0}$$

3.2. DIRECT METHOD

It can be seen how p_2 is independent of τ , so it can be written as:

$$p_2(\mu|\vec{x}, t) = p_2(\mu|\tau, \vec{x}, t) = \frac{a_\mu}{a_0}$$

To verify that these two equation are part of the pdf:

$$\int_0^\infty p_1(\tau|\vec{x}, t)d\tau = \int_0^\infty a_0 e^{-a_0 \tau} d\tau = 1 \quad \wedge \quad \sum_{\mu=1}^M p_2(\mu|\vec{x}, t) = \sum_{\mu=1}^M \frac{a_\mu}{a_0} = 1$$

The direct method uses $p_1(\tau|\vec{x}, t)$ to sample the firing time τ and $p_2(\mu|\vec{x}, t)$ to sample the reaction index μ . Since the two pdfs are independent the firing time and the reaction index can be sampled independently, so that the order of sampling does not effect the exactness of the direct method. The generated firing time τ and the next reaction firing R_μ are ensured to have the pdf $p(\tau, \mu|\vec{x}, t)$ specified by the stochastic simulation algorithm, so that the generated trajectories are exact.

3.2.1.1 Choice of the reaction

The selection of the next reaction index μ has probability $\frac{a_\mu}{a_0}$. Given M discrete probabilities $\frac{a_j}{a_0}$ with $j = 1, \dots, M$, the choice of the next reaction index:

$$\begin{aligned} \mu &= \arg \min_{\mu \in j=1, \dots, M} \sum_{j=1}^M \frac{a_j}{a_0} \geq r_1 = \\ &= \arg \min_{\mu \in j=1, \dots, M} \sum_{j=1}^M a_j \geq r_1 a_0 \end{aligned}$$

Where r_1 is a uniformly distributed random number $norm(0, 1)$. To select the next reaction firing R_μ , the direct methods accumulates the sum $\sum_{j=1}^\mu a_j$ until it finds the smallest index μ that satisfies that inequality.

3.2.1.2 Selection of the firing time

For the reaction of the firing time τ , consider its pdf $p_1(\tau|\vec{x}, t)$. It can be noted ho it is an exponential distribution with rate a_0 . So the firing time can be generated as:

$$\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$$

Where r_2 is a uniformly distributed random number $norm(0, 1)$.

3.2.2 The algorithm

The independent sampling of the firing time and of the reaction index are the basis of each simulation step of the direct method, outlined in algorithm 2.

3.2. DIRECT METHOD

Algorithm 2: Direct Method (DM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 while  $t < T_{\max}$  do  

6    $a_0 = 0$   

7   foreach  $R_j$  do  

8     compute  $a_j$   

9      $a_0 = a_0 + a_j$   

10  generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$   

11  select  $R_\mu$  with the smallest index  $\mu$  such that  $\sum_{j=1}^{\mu} a_j \geq r_1 a_0$   

12   $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$   

13   $\vec{X} = \vec{X} + \vec{v}_\mu$   

14   $t = t + \tau$ 

```

Lines 10-12 implement the sampling of the joint reaction probability density function of the next reaction firing and its firing time. The simulation needs two random number, the first is used to select the next reaction firing with probability $\frac{a_\mu}{a_0}$, while the second for the firing time. The state is then advanced to the new one and the time is moved to $t + \tau$.

3.2.2.1 Time complexity

The computational cost for the generation of random numbers, the firing time and the update of simulation time are constant. Moreover the update of the state can be considered constant as only a few species are involved in a reaction. Because of this the computational cost of the algorithm arises due to:

- The computation of reaction propensities due to state changes at lines 7-9.
- The selection of the next reaction firing at line 11.

The direct method computes M reaction propensities for each simulation step, so the time complexity for this step is of $O(M)$. The search for the next reaction in the worst case requires to sum up all the M reaction propensities, making the cost for searching the next reaction firing $O(M)$. Summing up the time complexity for each simulation step of the direct method is $O(M)$.

3.2.3 Enhanced direct method

The enhanced direct method EDM reduces the number of propensity computation for each simulation iteration, recomputing only the propensity of reactions that change. The detection of changes in the reaction propensity is based on the fact that the propensity of a reaction changes only when the population of the reactants involved in the reaction changes only then the population of the reactants involved are changed by the reaction firing. Only the propensity of reaction that have reactant

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population changed are recomputed. This is decided by analysing the dependency relationship between reactions.

3.2.3.1 Reaction dependency graph

A reaction R_j is dependent on a reaction R_μ if its propensity a_j is changed when R_μ fires. This relationship is collected and presented in a reaction dependency graph.

3.2.3.1.1 Some definitions

3.2.3.1.1.1 Reactants and products set

For each reaction R_j , with $j = 1, \dots, M$, define:

$$Reactants(R_j) = \{S_i | S_i \text{ is a reactant of } R_j\} \quad \wedge \quad Products(R_j) = \{S_i | S_i \text{ is a product of } R_j\}$$

3.2.3.1.1.2 Affects set

The set of species involved in the computation of the propensity a_j of a reaction R_j is:

$$Affects(R_j) = \{S_i | a_j \text{ changes if population of } S_i \text{ changes}\}$$

3.2.3.1.1.3 Mass action kinetics

For mass action kinetics, because the mass action propensity a_j of reaction R_j is proportional to its reactants:

$$Affects(R_j) = Reactants(R_j)$$

3.2.3.1.1.4 AffectedBy set

The set of species whose population changes by firing reaction R_j is:

$$AffectedBy(R_j) = \{S_i | \text{Population of } S_i \text{ is changed if firing } R_j\}$$

3.2.3.1.1.5 Population of AffectedBy

For each reaction R_j it is:

$$AffectedBy(R_j) \subseteq Reactants(R_j) \cup Products(R_j)$$

This is because $AffectedBy(R_j)$ includes species that are consumed and produced by reaction R_j excluding any species whose population is conserved.

3.2.3.1.2 Definition of the reaction dependency graph

Let \mathcal{R} be the set of reactions in the biochemical reaction network. The reaction dependency graph $G(V, E)$ is a directed graph with the vertex set $V = \mathcal{R}$ and the edge set E contains directed edges $e(R_j, R_k)$ from a reaction R_j to another reaction R_k if:

$$AffectedBy(R_j) \cap Affects(R_k) \neq \emptyset$$

All self-edges $e(R_j, R_j)$ belong to E .

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3.2.3.1.3 Dependent reactions The set of reactions that are dependent on reaction R_j by the reaction dependency graph G is defined such that:

$$\text{Dependents}(R_j) = \{R_k | \exists \text{ a directed edge } e(R_j, R_k) \in G\}$$

The reaction dependency graph G determines the reaction for which propensities must be recomputed after firing. The number of reaction in the *Dependents* set is equal to the out-degree of the reaction in the dependency graph.

3.2.3.2 Algorithm

In the EDM algorithm the reaction dependency graph is the first thing built. This will be a static structure independent on the time evolution of the system and will be stored with a cost $O(M^2)$. The computation of propensity of all the reaction is performed only at the beginning of the simulation. For each iteration the selection is the same as in DM, then the new propensity for each reaction $R_j \in \text{Dependents}(R_\mu)$ is computed. The algorithm is presented in 3.

Algorithm 3: Enhanced Direct Method (EDM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$ 
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3 build the reaction dependency graph  $G$ 
4  $t = 0$ 
5  $\vec{X} = \vec{x}_0$ 
6 foreach  $R_j$  do
7   compute  $a_j$ 
8    $a_0 = a_0 + a_j$ 
9 while  $t < T_{\max}$  do
10   generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$ 
11   select  $R_\mu$  with the smallest index  $\mu$  such that  $\sum_{j=1}^{\mu} a_j \geq r_1 a_0$ 
12    $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$ 
13    $\vec{X} = \vec{X} + \vec{v}_\mu$ 
14    $t = t + \tau$ 
15   foreach  $R_j \in \text{Dependents}(R_\mu)$  do
16     compute  $a_j^{new}$ 
17      $a_0 = a_0 + (a_j^{new} - a_j)$ 
18      $a_j = a_j^{new}$ 
```

In this way the propensity updates become local. Let D be the average number of reactions depending in a reaction, the cost of the propensity update for a simulation loop becomes $O(D)$, considering that $D < M$, so the propensity update in EDM is more efficient than in DM.

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3.2.4 Improvements for Direct Method

3.2.4.1 Direct method with sorted reaction

The principle of the direct method with sorted reaction is to reduce the search depth of the direct method by re-indexing reactions, reducing the search depth of reactions that happens more frequently, improving simulation performance.

3.2.4.1.1 Optimized direct method The optimized direct method reduces the average search depth of the next reaction firing. This is done because in many biochemical networks, some reactions fire much more frequently than others.

3.2.4.1.1.1 Average search depth The average search depth S_m is the average number of operation performed for the selection of the next reaction firing:

$$S_M = \frac{\sum_{j=1}^M j n_j}{\sum_{j=1}^M n_j}$$

Where:

- j is the search index of reaction R_j .
- n_j is the number of times that R_j fires during the simulation.

These two values are not known so to order the reactions $\langle n_j \rangle$ the average estimation of n_j is used to order reaction. This is computed by some short pre-simulation runs.

3.2.4.1.1.2 Algorithm Optimized direct method is implemented as in algorithm 4.

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Algorithm 4: Optimized Direct Method (ODM)()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3 build the reaction dependency graph  $G$   

4 perform a few DM pre-simulation runs to estimate  $\langle n_j \rangle$  of each reaction  

5 order reaction indices such that  $j < k$  if  $\langle n_j \rangle > \langle n_k \rangle$   

6  $t = 0$   

7  $\vec{X} = \vec{x}_0$   

8 foreach  $R_j$  do  

9   | compute  $a_j$   

10  |  $a_0 = a_0 + a_j$   

11 while  $t < T_{\max}$  do  

12   | generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$   

13   | select  $R_\mu$  with the smallest index  $\mu$  such that  $\sum_{j=1}^{\mu} a_j \geq r_1 a_0$   

14   |  $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$   

15   |  $\vec{X} = \vec{X} + \vec{v}_\mu$   

16   |  $t = t + \tau$   

17   | foreach  $R_j \in \text{Dependents}(R_\mu)$  do  

18     |   | compute  $a_j^{new}$   

19     |   |  $a_0 = a_0 + (a_j^{new} - a_j)$   

20     |   |  $a_j = a_j^{new}$ 

```

3.2.4.1.1.3 Discussion In the case of a fixed number of bits the sum of the biggest propensities placed in the front of the search list may be not enough to account for the rest: the reactions with very small propensity will never fire. Moreover the pre-simulation introduces an additional computational burden to the simulation. Moreover ODM assumes that the reaction order determined by the pre-simulation runs will characterize the long-term reaction behaviour, which could not be true.

3.2.4.1.2 Sorting direct method The sorting direct method SDM is a variant of ODM that does not use pre-simulation runs by maintaining an approximately sorted order of reaction. The ordering is built dynamically during the simulation run: the index of a reaction whenever it is selected to fire is dynamically bubbled up one step ahead in the reaction list. The reactions that have just occurred are put towards the top of the search list.

3.2.4.1.2.1 Algorithm The sorting direct method is implemented as in algorithm 5.

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Algorithm 5: Sorting Direct Method (SDM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 build the reaction dependency graph  $G$   

6 foreach  $R_j$  do  

7   | compute  $a_j$   

8   |  $a_0 = a_0 + a_j$   

9 while  $t < T_{\max}$  do  

10  | generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$   

11  | select  $R_\mu$  with the smallest index  $\mu$  such that  $\sum_{j=1}^{\mu} a_j \geq r_1 a_0$   

12  |  $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$   

13  |  $\vec{X} = \vec{X} + \vec{v}_\mu$   

14  |  $t = t + \tau$   

15  | foreach  $R_j \in \text{Dependents}(R_\mu)$  do  

16    |   | compute  $a_j^{new}$   

17    |   |  $a_0 = a_0 + (a_j^{new} - a_j)$   

18    |   |  $a_j = a_j^{new}$   

19  | if  $\mu > 1$  then  

20    |   | Swap  $R_\mu$  and  $R_{\mu-1}$  in the reaction list

```

3.2.4.1.2.2 Discussion The swapping step adds overhead to each simulation step, but it is negligible. SDM is thus suited to deal with the simulation of networks where the propensities change sharply.

3.2.4.2 Direct method with Multi-level search

The main bottleneck of DM is that the search for next reaction firing is slow in large reaction models. The multi-level search is an effort to reduce the time complexity of DM for large systems. The search problem is divided into smaller sub-problem partitioning the M reactions into L groups G_1, \dots, G_L . Each group G_l contains k_l reactions. Let a^l be the sum of propensities of reactions in group G_l :

$$a^l = \sum_{R_j \in G_l} a_j$$

It is obvious that:

$$a_0 = \sum_{l=1}^L a^l$$

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The selection of the next reaction firing is in two steps. First a group G_α is selected with probability $\frac{a^\alpha}{a_0}$. Then the next reaction firing R_μ is selected with probability $\frac{a_\mu}{a^\alpha}$ conditioning on the selected group G_α .

3.2.4.2.1 Exactness of the multi level search The next reaction R_μ in the group G_α that is selected by the multi-level search has probability $\frac{a_\mu}{a_0}$. Let $\mathbb{P}\{R_\mu\}$ be the probability of selecting the reaction R_μ . This can be expanded as:

$$\mathbb{P}\{R_\mu\} = \mathbb{P}\{G_\alpha\}\mathbb{P}\{R_\mu|G_\alpha\} = \frac{a^\alpha}{a_0} \frac{a_\mu}{a^\alpha} = \frac{a_\mu}{a_0}$$

3.2.4.2.2 Implementation An implementation to select the group index and the reaction index requires two random numbers:

$$\alpha = \arg \min_{\alpha \in l=1, \dots, L} \sum_{l=1}^{\alpha} a^l \geq r_1 a_0$$

And:

$$\mu = \arg \min_{\mu \in k=1, \dots, M} \sum_{k=1}^{\mu} a_k \geq r_2 a^\alpha$$

$G_\alpha = \{R_j, \dots, R_{j+k_\alpha}\}$

The need for r_2 can be avoided by recycling r_1 :

$$\frac{r_1 a_0 - \sum_{l=1}^{\alpha-1} a^l}{a^\alpha}$$

Is a uniformly distributed random number. SO r_1 is rescaled to select the next reaction firing in the group.

3.2.4.2.3 Algorithm The direct method with multi-level search is implemented as in algorithm 6.

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Algorithm 6: Direct method with multi level search()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$ 
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3 build the reaction dependency graph  $G$ 
4 partition  $M$  reactions into  $L$  groups  $\{G_1, \dots, G_L\}$ 
5  $t = 0$ 
6  $\vec{X} = \vec{x}_0$ 
7 foreach  $G_l$  do
8    $a^l = 0$ 
9   foreach  $R_j \in G_l$  do
10    | compute  $a_j$ 
11    |  $a^l = a^l + a_j$ 
12   |  $a_0 = a_0 + a^l$ 
13 while  $t < T_{\max}$  do
14   generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$ 
15   select  $G_\alpha$  with the smallest index  $\alpha$  such that  $\sum_{l=1}^{\alpha} a^l \geq r_1 a_0$ 
16    $r_1 = \frac{r_1 a_0 - \sum_{l=1}^{\alpha-1} a^l}{a^\alpha}$ 
17   select  $R_\mu$  with the smallest index  $\mu$  such that  $\sum_{k=1}^{\mu} a_k \geq r_1 a^\alpha$   

       $G_\alpha = \{R_j, \dots, R_{j+n}\}$ 
18    $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$ 
19    $\vec{X} = \vec{X} + \vec{v}_\mu$ 
20    $t = t + \tau$ 
21   foreach  $R_j \in \text{Dependents}(R_\mu)$  do
22    | compute  $a_j^{new}$ 
23    |  $a^l = a^l + (a_j^{new} - a_j)$ 
24    |  $a_j = a_j^{new}$ 

```

3.2.4.2.4 Discussion To analyse the time complexity of the multi-level search assume that M reactions are partitioned into $L = \lceil \frac{M}{k} \rceil$ groups and each group contains $k_l = k$ reactions. The time complexity has two parts:

- Searching for a group $O\left(\frac{M}{k}\right)$.
- Searching for a reaction within the group $O(k)$.

The total time complexity is then

$$O\left(\frac{M}{k}\right) + O(k) = O(\max\left\{\frac{M}{k}, k\right\})$$

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The total time is minimized by taking $k = c\sqrt{M}$, so that the minimal time complexity per reaction event is $O(\sqrt{M})$. The multi-level search can be further expanded partitioning the groups into sub-groups, introducing the multi-dimensional search method.

3.2.4.3 Direct method with tree-based search

The tree-based search refines the multi-level search. The finest partitioning of reaction is when the lowest level has at most two reaction creating a binary tree structure. Each node has two children or zero and the leaves hold reaction propensity, while internal node hold the sums of the values in their child nodes. The root of the tree holds a_0 .

3.2.4.3.1 Dimension of a complete tree A complete binary tree with M leaves has $2M - 1$ nodes. Let P be the number of internal nodes. In a complete tree each internal node has two children, hence the number of edges is $2P$. Also the edges are $M + P - 1$, so $P = M - 1$, so in conclusion the number of nodes is $P + M = 2M - 1$.

3.2.4.3.2 Implementation of the tree The tree can be implemented by an array with $2M - 1$ elements. The number of reaction M has to be even, and if it is not a dummy node with propensity 0 is added to the end of the array. Algorithm 7 outlines how the tree is built: it happens recursively from the leaves to the root, observing that a node in i will have children in position $2i$ and $2i + 1$.

Algorithm 7: `build_tree(position)`

- 1 **Input:** an array TREE with $2M - 1$ elements where elements from M to $2M - 1$ are filled with M reaction propensities and a starting position.
 - 2 **Output:** The complete binary tree represented by the array TREE.
 - 3 **if** $position < M$ **then**
 - 4 **build_tree**($2 \cdot position$)
 - 5 **build_tree**($2 \cdot position + 1$)
 - 6 $TREE[position] = TREE[2 \cdot position] + TREE[2 \cdot position + 1]$
-

3.2.4.3.3 Tree-based search The tree-based search for the next reaction firing R_μ given $s = ra_0$ starts by selecting the next branch of the tree by comparing the search value s with the value stored in the left child of the current node. Then the search selects the left branch if the value is less than the one stored in the left child of the node, otherwise the search chooses the right branch. If the right branch is selected the search value is subtracted by the value stored in the current node. This proceeds recursively until it reaches a leaf and the reaction stored in that leaf is returned with the correct probability $\frac{a_\mu}{a_0}$. This procedure is outlined in 8.

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Algorithm 8: `search_tree(position, s)`

1 **Input:** A complete binary tree represented by the array TREE, and integer position and a search value s
2 **Output:** The leaf of the complete binary tree which stores the next reaction firing.
3 **if** $position \geq$ **then**
4 **return** position
5 **else if** $TREE[2 \cdot position] \geq s$ **then**
6 **search_tree**($2 \cdot position$, s)
7 **else**
8 $s = TREE[position] - s$
9 **search_tree**($2 \cdot position + 1$, s)

3.2.4.3.4 Updating the tree The system is updated after the selected reaction fires. The nodes of the tree will update their propensity value. For each reaction depending on the reaction firing according to the dependency graph G , its new propensity is computed and the difference is propagated for every of their paths. To optimize this implementation, reactions dependent on each other should be placed as close as possible on the tree. This procedure is outlined in algorithm 9.

Algorithm 9: `update_tree(position, c)`

1 **Input:** A complete binary tree represented by the array TREE.
2 **Output:** The complete binary tree updated by the reaction firing.
3 $TREE[position] = TREE[position] + C$
4 **if** $position$ is not root **then**
5 **update_tree**($\lfloor \frac{i}{2} \rfloor$, c)

3.2.4.3.5 Algorithm The whole procedure is implemented in the algorithm 10.

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Algorithm 10: Direct method with tree-based search()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3 build the reaction dependency graph  $G$   

4  $t = 0$   

5  $\vec{X} = \vec{x}_0$   

6 foreach  $R_l$  do  

7   | compute  $a_j$   

8 build TREE structure for  $M$  reaction propensities with 7  

9 while  $t < T_{\max}$  do  

10  | generate two random numbers  $r_1, r_2 \sim \text{norm}(0, 1)$   

11  | select next reaction firing  $R_\mu$  by algorithm 8 with  $s = r_1 a_0$   

12  |  $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$   

13  |  $\vec{X} = \vec{X} + \vec{v}_\mu$   

14  |  $t = t + \tau$   

15  | foreach  $R_j \in \text{Dependents}(R_\mu)$  do  

16    |   | compute  $a_j^{new}$   

17    |   | update the TREE by algorithm 9 with  $c = a_j^{new} - a_j$   

18    |   |  $a_j = a_j^{new}$ 

```

3.2.4.3.6 Discussion The search and updated are related to the height of the tree, logarithmic in the number of reactions. So the total computational cost for each reaction event is $O(\log(M))$.

3.2.4.3.7 Tree with optimal height The computational cost for selecting the next reaction firing in a complete tree is not the optimal average-case performance. Let C be a tree structure.

3.2.4.3.7.1 Average number of comparison The average number of comparison performed during the search in tree C is:

$$T_m(C) = \sum_{j=1}^M w_j D_j$$

Where:

- M is the total number of reactions in the leaves.
- w_j is a weight related to the probability that reaction R_j is selected to fire.
- D_j is the depth of leaf R_j .

3.2.4.3.7.2 Complete tree When the tree C is complete the depth D_j is the same for all j . This leads to the fact that picking a fast reaction requires the same computational power of picking a slow one, leading to a non-optimal $T_M(C)$.

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3.2.4.3.7.3 Huffman tree The minimization of $T_M(C)$ leads to the construction of the Huffman tree. The leaves in this type of tree with large propensity values will be closer than the leaves with small values. This is built by merging trees in a forest, populated initially by trees with one node. At each step the two trees with roots p and q having the smallest weight w_p and w_q are merged creating the new root pq with weight $w_{pq} = w_p + w_q$. The process stops when only one tree is found such that $D_{pq} + 1 = D_q = D$, where p, q, pq are the nodes involved in a merge such that:

$$\begin{aligned} T_M(C) &= \sum_{\substack{j=1 \\ j \neq p,q}}^M w_j D_j + w_p D_q = \\ &= \left(\sum_{\substack{j=1 \\ j \neq p,q}}^M w_j D_j + w_{pq} D_{pq} \right) + w_{pq} = \\ &= T_{M-1}(C) + w_{pq} \end{aligned}$$

This derivation allows to determine that the Huffman tree gives the minimum value of $T_M(C)$. This is proven by induction on M . Consider the base case with $M = 2$, this is easy to check. By the inductive hypothesis, the Huffman tree for $M - 1$ gives the optimum value for $T_{M-1}(C)$. Suppose by contradiction that the Huffman tree for M is not optimal, so there is some tree having the total number of comparison $T'_M(C)$ such that $T'_M(C) < T_M(C)$. Without loss of generality the smallest weights are placed at the lowest level. Let p and q be the nodes with the smallest weights and label their parent pq . Using the derivation this gives:

$$T'_{M-1}(C) + w_{pq} < T_{M-1}(C) + w_{pq}$$

Then $T'_{M-1}(C) < T_{M-1}(C)$, contradicting the inductive hypothesis.

3.2.4.3.7.4 Building the Huffman tree To build a Huffman tree an array with size $2M - 1$ is considered and each node has two children. However M does not need to be even. The leaves are between M and $2M - 1$. Each element in the array points to its left and right child and an additional field parent points to the parent of the node. To extract the nodes with minimal weights a binary heap is used, such that each element is (i, w_i) , where i is the index of a node in the tree and the weight w_i is used as the key for ordering the heap. A heap is a tree-based data structure that satisfies the heap property: the key of a parent node is smaller than the key of its child nodes. The implementation for this procedure is presented in algorithm 11

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Algorithm 11: build_huffman_tree(*position*)

```

1 Input: an array TREE with  $2M - 1$  elements where elements from  $M$  to  $2M - 1$  are filled
   with  $M$  reaction propensities
2 Output: The Huffman tree represented by the array TREE.
3 build binary heap  $H$  with elements  $(M, w_1), \dots, (2M - 1, w_M)$  ordered according to  $W_j$ 
4 for position =  $M - 1$  to 1 do
5   extract top element  $(p, w_p)$  from  $H$ 
6   extract top element  $(q, w_q)$  from  $H$ 
7    $TREE[position].VALUE = TREE[p].VALUE + TREE[q].VALUE$ 
8    $TREE[position].LEFT = p$ 
9    $TREE[position].RIGHT = q$ 
10  insert(position,  $w_p + w_q$ ) into  $H$ 
11   $TREE[p].PARENT = position$ 
12   $TREE[q].PARENT = position$ 

```

The same binary search and propagation update are applied to search and update the propensities of the reactions.

3.2.4.3.7.5 Selecting the weight The weight function w_j can be the propensity function a_j because it allows to reduce the time spent to find the next reaction, however reaction firing could make the tree no longer optimal, so it should be rebuilt. To balance the expensive operation of re-building with the non-optimal tree, the non-optimal tree is used for some number of steps. The choice for this step number only affect performance and not exactness. There are two approaches to do so:

- Fixed time tree rebuilding.
- Adaptive time tree rebuilding.

3.2.4.3.7.6 Fixed time tree rebuilding In fixed time tree rebuilding the tree structure is built every k steps. To predict the changes in the reaction propensities during the k steps the weights can be modified assigning a higher weight to those reaction that are more likely to change.

Conflicts and Favours set For a reaction R_j define:

$$Conflicts(R_j) = \{R_k | (R_j \in Dependents(R_k)) \wedge (Reactants(R_k) \cap Reactants(R_j) \neq \emptyset)\}$$

$$Favors(R_j) = \{R_k | (R_j \in Dependents(R_k)) \wedge (Products(R_k) \cap Reactants(R_j) \neq \emptyset)\}$$

Dependency graph In terms of the dependency graph:

$$|Conflicts(R_j)| + |Favors(R_j)| = \text{in degree of } R_j$$

Estimating changes of propensity After a reaction firing, the probability that R_j will increase or decrease is estimated as $\frac{|Conflicts(R_j)|}{M}$ or $\frac{|Favors(R_j)|}{M}$. For k simulation steps, the estimated weight of reaction R_j is:

$$w_j(a_j, k) = a_j + \alpha_1 k \frac{|Favors(R_j)|}{M} + \alpha_2 k \frac{|Conflicts(R_j)|}{M}$$

Where α_1 and α_2 are parameters denoting the amount of average change.

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3.2.4.3.7.7 Adaptive time tree rebuilding In adaptive time tree rebuilding the tree is rebuilt when a significant change has occurred. To detect the abrupt change in propensities a predefined value δ , the acceptance threshold defines the largest change which does not require an immediate tree rebuilding. The difference in propensity after a reaction R_j firing is $c_j = a_j^{new} - a_j$. If $c_j \geq \delta$ the Huffman tree should be rebuilt. To account for many small changes a cumulative sum of all the propensity changes s_j since the last rebuilt is computed and compared against the acceptance threshold to decide whether to rebuild the tree.

3.2.4.4 Direct method with composition-rejection search

The composition-rejection CR search employs the partitioning of reaction into groups, but the selection of the next reaction is performed through an acceptance-rejection sampling. The reactions are partitioned into L groups so that $R_j \in G_l$ if a_j satisfies $2^{u_{l-1}} \leq a_j \leq 2^{u_l}$ in which u_l is selected such that $u_l = \lceil \log_2(a_j) \rceil$. If a_{\min} and a_{\max} , the global minimum and maximum propensities, are known, then $L = \lceil \log_2 \left(\frac{a_{\max}}{a_{\min}} \right) \rceil$ for the whole simulation. These two bounds on a can be estimated through physical reasoning. Where this is not possible L must be increased during the simulation.

3.2.4.4.1 Search for the next reaction Let $a^l = \sum_{R_j \in G_l} a_j$ be the sum of the propensity in group G_l . The total propensity a_0 can be computed as:

$$a_0 = \sum_{l=1}^L a^l$$

The search is composed of two steps.

3.2.4.4.1.1 First step In the first step a group G_α is selected with probability $\frac{a^l}{a_0}$. This can be performed accumulating values a^l until the smallest index α is found such that:

$$\sum_{l=1}^{\alpha} a^l \geq r_1 a_0$$

The tree-based search can be applied to select the group.

3.2.4.4.1.2 Second step The second step is done through an acceptance-rejection sampling with the chosen envelope 2^{u_α} . A random and uniform reaction index $\mu \in G_\alpha$ is computed: $\mu = [r_2 |G_\alpha|]$, where $|G_\alpha|$ is the size of G_α and r_2 is a random number. The selected reaction is tested to accept with probability $\frac{a_\mu}{2^{u_\alpha}}$: a random number r_3 is generated and compared against $\frac{a_\mu}{2^{u_\alpha}}$. r_2 can be recycled noting that $r_3 = r_2 |G_\alpha| - \mu$ is uniformly distributed in $[0, 1]$. If $\frac{a_\mu}{2^{u_\alpha}} \leq r_3$ holds, R_μ is accepted to fire. Otherwise the reaction is rejected and a new random reaction index is generated and the check is performed again. This is repeated until there is an accepted R_μ . The acceptance probability is bound to $\frac{1}{2}$: $\frac{a_\mu}{2^{u_\alpha}} \geq \frac{1}{2}$ by definition.

3.2.4.4.2 Algorithm An implementation of this method is found in algorithm 12. The rejection test is repeated on average two times: the acceptance rate is bounded by $\frac{1}{2}$. Moreover after a reaction firing the propensity must be updated and it could be that a new reaction falls outside of the current bound, so it must be moved to an appropriate group.

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Algorithm 12: Direct Method with Composition-Rejection Search()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 build the dependency graph  $G$   

6 partition  $M$  reactions into  $L$  groups  $\{G_1, \dots, G_L\}$  such that  $R_j \in G_l$  if  $2^{u_l-1} \leq a_j \leq 2^{u_l}$   

7  $a_0 = 0$   

8 foreach  $G_l$  do  

9    $a^l = 0$   

10  foreach  $R_j \in G_l$  do  

11    compute  $a_j$   

12     $a^l = a^l + a_j$   

13   $a_0 = a_0 + a^l$   

14 while  $t < T_{\max}$  do  

15   generate a random number  $r_1 \sim \text{norm}(0, 1)$   

16   select  $G_\alpha$  with the smalles group index  $\alpha$  such that  $\sum_{l=1}^{\alpha} a^l \geq r_1 a_0$   

17   repeat  

18     generate a random number  $r_2 \sim \text{norm}(0, 1)$   

19      $\mu = [r_2 | G_\alpha |]$   

20      $r_2 = r_2 | G_\alpha | - \mu$   

21     until  $r_2 \leq \frac{a_\mu}{2^{u_\alpha}}$   

22     generate a random number  $r_3 \sim \text{norm}(0, 1)$   

23      $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$   

24      $\vec{X} = \vec{X} + \vec{v}_\mu$   

25      $t = t + \tau$   

26     foreach  $R_j \in \text{Dependents}(R_\mu)$  do  

27       update  $a_j$   

28       if  $a_j \notin [2^{u_l-1}, 2^{u_l}]$  then  

29         move  $R_j$  from  $G_l$  to an appropriate  $G_m$   

30         updated  $a^l$  and  $a^m$   

31       else  

32         update  $a^l$   

33       update  $a_0$ 
```

3.2.4.4.3 Discussion The selected base 2 in the partition can be chosen arbitrarily, with the dimension of groups and the number of rejections increasing with the base. Moreover efficient data structures are needed to implement the movement of reactions between groups: this should support dynamic memory allocation operation. In addition a hash table should be used to support fast lookup of a reaction in a group. For adding a reaction to a group, the group size is increased and

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the reaction is added at the end of the group. When deleting a reaction, the reaction at the end of the group replaces it and the group size is decremented. After each of this two operations, the hash table is updated.

3.2.4.4.3.1 Computational cost The computational cost is composed by the search for the group, proportional to the number of groups $O(L)$ and the cost for selecting the next reaction, which is constant. Because the average number of rejection tests is bound by 2, the time is $O(L)$ and is independent of the number of reactions M . If $L \ll M$ and is bounded by a small constant the search for the next reaction firing is $O(1)$.

3.2.5 Partial-propensity direct method

The partial propensity direct method PDM requires that reactions must be elementary and their propensities follow the mass action kinetics. Mass action propensities are factorized and the partial propensities related to common reactants are grouped to facilitate the selection of the next reaction firing. Let π_j^i the partial propensity of a reaction R_j with respect to reactant S_i , this is defined as the propensity per molecule of reactant S_i .

3.2.5.1 Partial propensities of elementary reactions

- Synthesis reaction ($\emptyset \rightarrow$ products): propensity $a_j = c_j$ and partial propensity $\pi_j^0 = c_j$.
- Unimolecular reaction ($S_i \rightarrow$ products): propensity $a_j = c_j X_i$ and partial propensity $\pi_j^i = c_j$.
- Bimolecular reaction ($S_i + S_k \rightarrow$ products): propensity $a_j = c_j X_i X_k$ and partial propensity $\pi_j^i = c_j X_k$ and $\pi_j^{(k)} = c_j X_i$.
- Dimerization reaction ($2S_i \rightarrow$ products): propensity $a_j = \frac{1}{2} c_j X_i (X_i - 1)$ and partial propensity $\pi_j^i = \frac{1}{2} c_j (X_i - 1)$.

3.2.5.2 Storing the partial propensities

The partial propensities related to a species S_i are grouped into a group Π_i , such that the structure:

$$\Pi = \{\Pi_i\}_{i=0}^N$$

Stores all of them and is a matrix implemented as an array of arrays. It has $N + 1$ rows in which the i -th row stores the partial propensities related to species S_i , while the 0-th row stores all the partial propensities for synthesis reactions. In the case of a bimolecular reaction one of the two partial propensities has to be dropped.

3.2.5.2.1 Minimizing updates To minimize updates the partial propensities are stored with respect to the reactant involved in a larger number of reaction: before building Π , the species are re-indexed such that for each pair of them S_i and S_k , $i < k$ if the number of reactions involving S_i is greater than S_k . Then PDM stores partial propensity of a bimolecular reaction with respect to the reactant with smaller index.

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3.2.5.3 Group-sum array

The sum $\Lambda_i = \sum_j \Pi_{i,j}$ gives the sum of partial propensities of reactions R_j sharing common reactant S_i . This is the group-sum array and is used to store the sum of partial propensities in group. $\Omega_i = X_i \Lambda_i$, where X_i is the population of S_i will be the sum of propensities of reaction having species S_i as the common reactant. The array $\Omega = \{\Omega_i\}_{i=0}^N$ to store the sum of propensities of gropus. The total propensity is computed as:

$$a_0 = \sum_{i=0}^N \Omega_i$$

3.2.5.4 Reaction lookup

A reaction is identified by the group index i and the element j in a group Π_i . To facilitate the lookup of a reaction given the element j , a lookup table \mathbf{L} is used to store the reaction indices of corresponding partial propensities in Π . It has the same structure as Π and is implemented as an array of arrays. The index of reaction with element index j in group i of Π is identified as \mathbf{L}_{ij} , moreover three additional lookup table are used to facilitate the update of Π , Λ and Ω after a reaction firing:

- $\mathbf{U}^{(1)}$ is an array of M arrays in which array j contains the indices of species involved in R_j .
- $\mathbf{U}^{(2)}$ is an array of M arrays in which the array j contains the amount of change in population of the corresponding species in $\mathbf{U}^{(1)}$.
- $\mathbf{U}^{(3)}$ is an array of N arrays in which array k contains pairs of group indices and element indices of all entry in Π that depend on species k . Each element in the row k is a pair denoting the partial propensity $\Pi_{i,j}$ dependent in X_k .

3.2.5.5 Selecting the reaction firing

PDM selects R_μ in two steps. Let r_1 b a uniformly distributed random number in $norm(0, 1)$.

3.2.5.5.1 First step

Search for the group index p , with $0 \leq p \leq N$:

$$p = \arg \min_{i \in p} \sum_{i=0}^p \Omega_i \geq r_1 a_0$$

3.2.5.5.2 Second step

Search for an element index q , with $q \geq 1$ such that:

$$q = \arg \min_{i \in q} \left(X_p \sum_{j=1}^q \Pi_{p,j} + \sum_{i=0}^p \Omega_i - \Omega_p \right) \geq r_1 a_0$$

Or:

$$q = \arg \min_{i \in q} \Pi_{o,j} \geq \Psi$$

Where:

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$$\Psi = \frac{r_1 a_0 - \sum_{i=0}^p \Omega_i + \Omega_p}{X_p}$$

Then p and q are used to retrieve the reaction firing index $\mu = \mathbf{L}_{p,q}$.

3.2.5.6 Exactness of PDM

The next reaction firing R_μ is selected by PDM having probability $\frac{a_\mu}{a_0}$. The selection of the reaction is performed by DM as:

$$\mu = \arg \min_{\mu \in j} \sum_{j=1}^{\mu} s_j \geq r_1 a_0$$

PDM identifies a reaction by a pair (p, q) where p is the group index and q the element index in Π by $\mu = \mathbf{L}_{p,q}$, then the equation can be re-written as:

$$(p, q) = \arg \min_{p \in i \wedge q \in j} \sum_{i=0}^p \sum_j a_{\mathbf{L}_{p,j}} \geq r_1 a_0$$

That can be broken down in:

$$p = \arg \min_{p \in i} \sum_{i=0}^p \sum_j a_{\mathbf{L}_{i,j}} \geq r_1 a_0$$

$$q = \arg \min_{q \in j} \sum_{i=0}^p \sum_j a_{\mathbf{L}_{i,j}} + \sum_{j=1}^q a_{\mathbf{L}_{p,j}} \geq r_1 a_0$$

Plugging into this two the definitions of Ω and Π they are equivalent to the one for the PDM seen before.

3.2.5.7 Algorithm

PDM is implemented as in algorithm 13.

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Algorithm 13: Partial-Propensity Direct Method (PDM)()

1 Input: a biochemical reaction network of M reactions in which each reaction R_j , $j = 1, \dots, M$ is accompanied with the state change vector \vec{v}_j and the propensity a_j , the initial state \vec{x}_0 at time 0 and the simulation ending time T_{\max} with mass action kinetics
2 Output: a trajectory of the biochemical reaction network, which is a collection of states $X(t)$ for time $0 \leq t \leq T_{\max}$
3 $t = 0$
4 $\vec{X} = \vec{x}_0$
5 build Π , Λ , Ω and \mathbf{L} , $\mathbf{U}^{(1)}$, $\mathbf{U}^{(2)}$ and $\mathbf{U}^{(3)}$
6 $a_0 = 0$
7 foreach $i \in \Omega$ **do**
8 $a_0 = a_0 + \Omega_i$
9 while $t < T_{\max}$ **do**
10 generate two random numbers $r_1, r_2 \sim \text{norm}(0, 1)$
11 select the smallest group index p such that $\sum_{i=0}^p \Omega_i \geq r_1 a_0$
12 $\Psi = \frac{r_1 a_0 - \sum_{i=0}^p \Omega_i + \Omega_p}{X_p}$
13 select R_μ with the smallest index q such that $\sum_{j=1}^q \Pi_{p,j} \geq \Psi$
14 $\mu = \mathbf{L}_{p,q}$
15 $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$
16 $\Delta a = 0$
17 foreach $k \in \mathbf{U}_\mu^{(1)}$ **do**
18 $l = \mathbf{U}_{\mu,k}^{(1)}$
19 $X_l = X_l + \mathbf{U}_{\mu,k}^{(2)}$
20 foreach $m \in \mathbf{U}_l^{(3)}$ **do**
21 $(i, j) = \mathbf{U}_{l,m}^{(3)}$
22 $\mu' = \mathbf{L}_{i,j}$
23 **if** $l \neq i$ **then**
24 $\Pi_{i,j} = \Pi_{i,j} + c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$
25 $\Lambda_i = \Lambda_i + c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$
26 **else if** $l = i$ **then**
27 $\Pi_{i,j} = \Pi_{i,j} + \frac{1}{2} c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$
28 $\Lambda_i = \Lambda_i + \frac{1}{2} c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$
29 $\Omega_{temp} = \Omega_i$
30 $\Omega_i = X_i \Lambda_i$
31 $\Delta a = \delta a + \Omega_i - \Omega_{temp}$
32 $\Delta a = \Delta a + X_k \Lambda_l - \Omega_l$
33 $\Omega_l = X_l \Lambda_l$
34 $a_0 = a_0 + \Delta a$
35 $t = t + \tau$

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3.2.5.7.1 Discussion

3.2.5.7.1.1 Time complexity The time complexity of the search for the next reaction firing has two parts:

- Selecting the group, which in the worst case travels $N + 1$ groups, in time $O(N)$.
- Selecting the element in the group, which is proportional to the number of reactions

sharing the same reactant. This is model dependent and bounded by a small constant. For elementary reactions the worst case is N , so the cost for this step is $O(N)$.

In total the time complexity for the search for the next reaction firing in PDM is $O(N)$.

3.2.5.7.1.2 Limitations The major limitation of PDM is that it works for a class of reactions involving at most two reactants with factorisable reaction propensities. For models with high-order reactions the propensity is not factorizable and they must be broken down into elementary reactions and the propensity computation has to be modified.

3.2.5.8 Partial propensity direct method with composition-rejection search

The partial propensity direct method with composition-rejection search PDM-CR is a variant of PDM where the selection of p and q are done through the composition-rejection approach. ‘ M ’ is grouped into L groups such that G_l stores group index i such that $2^{u_l-1} \leq \Omega_i < 2^{u_l}$ with $u_l = \lceil \log_2(\Omega_i) \rceil$. The sum of propensities in G_l is:

$$a^l = \sum_{i \in G_l} \Omega_i$$

For Π each i row is partitioned into K_i groups such that Q_k^i stores element index j such that $2^{v_k^i-1} \leq \Pi_{i,j} < 2^{v_k^i}$ with $v_k^i = \lceil \log_2(\Pi_{i,j}) \rceil$. The sum of partial propensity in Q_k^i is:

$$b_i^k = \sum_{j \in Q_k^i} \Pi_{i,j}$$

For each row of Π the relation $\sum_{k=1}^{K_i} b_i^k = \sum_j \Pi_{i,j} = \Lambda_i$ holds.

3.2.5.8.1 Selection of the next reaction firing The selection of the next R_μ consists of two CR searches: the first selects the group index p and the second the element index q .

3.2.5.8.1.1 Selecting group index To select the group index p two random numbers $r_1, r_2 \sim \text{norm}(0, 1)$ are sampled. Then a group G_α is selected with probability $\frac{a^\alpha}{a_0}$ with $a_0 = \sum_{l=1}^L a^l = \sum_{i=0}^N \Omega_i$ accumulating a^l until the smallest α is found such that:

$$\sum l = 1^\alpha a^l \geq r_1 a_0$$

Then r_2 is used to accept the group index p in G_α through an acceptance-rejection test with probability $\frac{\Omega_p}{2^{u_\alpha}}$.

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3.2.5.8.1.2 Selecting element index Once p has been selected q is selected through a second CR search. This requires two random numbers $r_3, r_4 \sim \text{norm}(0, 1)$. A group Q_β^p is selected with probability $\frac{b_p^\beta}{\Lambda_p}$ by a linear search. Then the element index q in the groups is selected through an acceptance-rejection test with probability $\frac{\Pi_{p,q}}{2^{v_p^\beta}}$.

3.2.5.8.2 Algorithm The PDM-CR implementation is outlined in algorithm 14

Algorithm 14: Partial-Propensity Direct Method with Composition-Rejection Search (PDM-CR)()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

 $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$  with mass action kinetics
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

 $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3  $t = 0$ 
4  $\vec{X} = \vec{x}_0$ 
5 build  $\Pi$ ,  $\Lambda$ ,  $\Omega$  and  $\mathbf{L}$ ,  $\mathbf{U}^{(1)}$ ,  $\mathbf{U}^{(2)}$  and  $\mathbf{U}^{(3)}$ 
6 partition  $\Omega$  into  $L$  groups  $G_1, \dots, G_L$  such that  $G_l$  contains  $\Omega_l$  if  $2^{u_l-1} \leq \Omega_i < 2^{u_l}$ 
7  $a_0 = 0$ 
8 foreach  $G_l \in \{G_1, \dots, G_L\}$  do
9    $a^l = \sum_{i \in G_l} \Omega_i$ 
10   $a_0 = a_0 + a^l$ 
11 for  $i = 0 \Rightarrow N$  do
12   partition  $\Pi_i$  into  $K_i$  groups  $Q_1^i, \dots, Q_{K_i}^i$  such that  $Q_k^i$  contains  $\Pi_{i,j}$  if  $2^{v_k^i-1} \leq \Pi_{i,j} < 2^{v_k^i}$ 
13   for  $i = 1 \rightarrow K_i$  do
14      $b_i^k = \sum_{\Pi_{i,j} \in Q_k^i} \Pi_{i,j}$ 
15 while  $t < T_{\max}$  do
16   generate a random number  $r_1 \sim \text{norm}(0, 1)$ 
17   select the smallest group  $G_\alpha$  such that  $\sum_{l=1}^{\alpha} a^l \geq r_1 a_0$ 
18    $\Psi = \frac{r_1 a_0 - \sum_{i=0}^p \Omega_i + \Omega_p}{X_p}$ 
19   select  $R_\mu$  with the smallest index  $q$  such that  $\sum_{j=1}^q \Pi_{p,j} \geq \Psi$ 
20 repeat
21   generate a random number  $r_2 \sim \text{norm}(0, 1)$ 
22    $p = [r_2 |G_\alpha|]$ 
23    $r_2 = r_2 |G_\alpha| - p$ 
24 until  $r_2 < \frac{\Omega_p}{2^{u_\alpha}}$ 
25 generate a random number  $r_3 \sim \text{norm}(0, 1)$ 
26 select the smallest group  $Q_\beta^p$  such that  $\sum_{k=1}^{\beta} b_p^k \geq r_3 \Lambda_p$ 
```

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```

1 Contd-While
2   repeat
3     generate a random number  $r_4 \sim \text{norm}(0, 1)$ ;
4      $q = [r_4|Q_\beta^p]|$ ;
5      $r_4 = r_4|Q_\beta^p| - q$ ;
6     until  $r_4 < \frac{\Pi_{p,q}}{2^{v_\beta}}$ ;
7      $\mu = \mathbf{L}_{p,q}$ ;
8      $\tau = \frac{1}{a_0} \ln \frac{1}{r_2}$ ;
9      $\Delta a = 0$ ;
10    foreach  $k \in \mathbf{U}_\mu^{(1)}$  do
11       $l = \mathbf{U}_{\mu,k}^{(1)}$ ;
12       $X_l = X_l + \mathbf{U}_{\mu,k}^{(2)}$ ;
13      foreach  $m \in \mathbf{U}_l^{(3)}$  do
14         $(i, j) = \mathbf{U}_{l,m}^{(3)}$ ;
15         $\mu' = \mathbf{L}_{i,j}$ ;
16        if  $l \neq i$  then
17           $\Pi_{i,j} = \Pi_{i,j} + c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$ ;
18           $\Lambda_i = \Lambda_i + c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$ ;
19        else if  $l = i$  then
20           $\Pi_{i,j} = \Pi_{i,j} + \frac{1}{2} c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$ ;
21           $\Lambda_i = \Lambda_i + \frac{1}{2} c_{\mu'} \mathbf{U}_{\mu,k}^{(2)}$ ;
22         $\Omega_{temp} = \Omega_i$ ;
23         $\Omega_i = X_i \Lambda_i$ ;
24         $\Delta a = \delta a + \Omega_i - \Omega_{temp}$ ;
25        updated group  $G_i$  and  $Q_j^i$ ;
26         $\Delta a = \Delta a + X_k \Lambda_l - \Omega_l$ ;
27         $\Omega_l = X_l \Lambda_l$ ;
28      updated group  $G_l$ ;
29       $a_0 = a_0 + \Delta a$ ;
30       $t = t + \tau$ ;

```

3.3 First reaction method

The first reaction method FRM is an alternative method to implement the Monte Carlo step of SSA. The next reaction firing R_μ and firing time τ are exact, so they are ensured to be distributed by the pdf $p(\tau, \mu | \vec{x}, t)$.

3.3.1 Tentative time

In FRM the reaction selected to fire is the one with the smallest tentative time. The tentative time is the firing time of the reaction assuming that no other reaction fires before. Let τ_j be the tentative

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time to the firing of R_j assuming that no other reaction fires before. Let $p(\tau_j|\vec{x}, t)$ be the pdf of τ_j such that $p(\tau_j|\vec{x}, t)d\tau_j$ gives the probability that R_j fires in the next infinitesimal time interval $[t + \tau_j, t + \tau_j + d\tau_j[$ assuming that no other reaction fires before. The formula of $p(\tau_j|\vec{x}, t)$, noting that there is only one R_j involved in the calculation is:

$$p(\tau_j|\vec{x}, t) = a_j e^{-a_j \tau_j}$$

From this the tentative time can be generated applying the inverse transforming method:

$$\tau_j = \frac{1}{a_j} \ln \left(\frac{1}{r_j} \right)$$

Where $r_j \sim \text{norm}(0, 1)$.

3.3.2 Exactness of the first reaction method

Let R_μ be the reaction having the smallest tentative time $\tau = \min_{j=1}^M \{\tau_j\}$ where each τ_j with $j = 1, \dots, M$ is distributed according to the pdf $p(\tau_j|\vec{x}, t) = a_j e^{-a_j \tau_j}$. Let $\tilde{p}(\tau, \mu|\vec{x}, t)d\tau$ be the probability that R_μ fires at time τ , then:

$$\tilde{p}(\tau, \mu|\vec{x}, t) = a_\mu e^{-a_\mu \tau}$$

The probability of R_μ which has the smallest time $\tau = \min_{j=1}^M \{\tau_j\}$ to fire at time τ is:

$$\tilde{p}(\tau, \mu|\vec{x}, t)d\tau = \mathbb{P}\{\tau < \tau_\mu < \tau + d\tau\} \mathbb{P}\{\tau_j > \tau \forall j \neq \mu\}$$

Where:

- $\mathbb{P}\{\tau < \tau_\mu < \tau + d\tau\}$ is the probability that R_μ with smallest tentative fire τ_μ fires in $[\tau, \tau + d\tau[$.
- $\mathbb{P}\{\tau_j > \tau \forall j \neq \mu\}$ is the probability that τ_j of R_j is greater than τ .

The first probability is directly derived from the definition of τ_μ as:

$$\mathbb{P}\{\tau < \tau_\mu < \tau + d\tau\} = a_\mu e^{-a_\mu \tau} d\tau$$

The second one is derived as follows:

$$\begin{aligned} \mathbb{P}\{\tau_j < \tau \forall j \neq \mu\} &= \mathbb{P}\left\{ \frac{1}{a_j} \ln \left(\frac{1}{r_j} \right) \forall i \neq \mu \right\} = \\ &= \mathbb{P}\{r_j < e^{-a_j \tau} \forall j \neq \mu\} = \\ &= \prod_{i=1 \wedge i \neq \mu}^M \mathbb{P}\{r_j < e^{-a_j \tau}\} = \\ &= \prod_{i=1 \wedge i \neq \mu}^M e^{-a_j \tau} \end{aligned}$$

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In which the generation of τ_j is considered, and the third step follows from the fact that r_j s are all independent and identically distributed random numbers. The last holds because the probability that a uniformly distribute random number from a unit interval is less than a number is equal to that number. Now, plugging the last to into \tilde{p} and recalling the definition of total propensity, the probability distribution of the next reaction firing is:

$$\tilde{p}(\tau, \mu | \vec{x}, t) = a_\mu e^{-a_\mu \tau} \left(\prod_{j=1 \wedge j \neq \mu} e^{-a_j \tau} \right) = a_\mu e^{-a_0 \tau}$$

3.3.3 Algorithm

An implementation of the steps of FRM is presented in algorithm 15. For each simulation iteration M uniformly distributed random numbers r_j are generated and used to compute the tentative time τ_j for all reactions. Then the reaction with the smallest time is selected to fire. Once the reaction has fired, the time and state are updated accordingly.

Algorithm 15: First Reaction Method (FRM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 while  $t < T_{\max}$  do  

6   foreach  $R_j$  do  

7     compute  $a_j$   

8     generate a random number  $r_j \sim \text{norm}(0, 1)$   

9      $\tau_j = \frac{1}{a_j} \ln \left( \frac{1}{r_j} \right)$   

10    select  $R_\mu$  with the smallest tentative time  $\tau = \min_{j=1}^M \{\tau_j\}$   

11     $\vec{X} = \vec{X} + \vec{v}_\mu$   

12     $t = t + \tau$ 
```

3.3.3.1 Time complexity

The time complexity is due to:

- Computing the tentative time of reactions.
This, for M reaction, is done in $O(M)$ time.
- Searching for the reaction with the small-
est tentative time. This is also $O(M)$ as
they can be linearly compared as they are
generated.

The time complexity is thus $O(M)$ for a time step and this algorithm is easy to parallelize. However it is often slower than DM because a large number of random numbers are required at each iterations. FRM is therefore slower than DM if the number of reactions $M \geq 2$.

3.3. FIRST REACTION METHOD

3.3.4 First family method

The first family method FFM is a generalization of DM and FRM methods. It partitions M reactions into L families. Each F_l contains k_l reactions, that can be different between families. L and k_l are tunable parameters. Note that because the partition is complete $\sum_{l=1}^L k_l = M$.

3.3.4.1 Next reaction event

The next reaction event in FFM is a pair (α, μ) denoting R_μ in family F_α . The selection is performed in two steps:

- Selection of the family.
- Selection of the reaction.

3.3.4.1.1 Selection of the family The selection is performed in two steps: a family with the smallest tentative time is selected. The tentative time of F_l is generated from an exponential distribution with rate equal to the sum of reaction propensities in the family. Let $a^l = \sum_{R_j \in F_l} a_j$ be the sum of propensities, then the tentative time will be computed as:

$$\tau_l = \frac{1}{a^l} \ln \left(\frac{1}{r_l} \right)$$

Where $r_l \sim \text{norm}(0, 1)$.

3.3.4.1.2 Selection of the reaction Let F_α be the family with the smallest tentative time: $\tau = \min_{l=1}^L \{\tau_l\}$. Conditioning on the selected F_α , R_μ is selected with probability $\frac{a_\mu}{a^\alpha}$. A DM search is applied to find the next reaction:

$$\mu = \arg \min_{k \in F_\alpha} \sum_{\substack{k=j \\ F_\alpha = \{R_j, \dots, R_{j+k\alpha}\}}}^{\mu} a_k \geq r a^\alpha$$

Where $r \sim \text{norm}(0, 1)$.

3.3.4.2 Algorithm

An implementation of the FFM is presented in algorithm 16. For each simulation step, L random number are required to compute the tentative times and an additional one is used to select the next reaction firing.

3.4. NEXT REACTION METHOD

Algorithm 16: First Family Method (FFM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 partition  $M$  reactions into  $L$  families  $\{F_1, \dots, F_L\}$   

6 while  $t < T_{\max}$  do  

7   foreach  $F_l$  do  

8      $a^l = 0$   

9     foreach  $R_j$  do  

10    compute  $a_j$   

11     $a^l = a^l + a_j$   

12    generate a random number  $r_l \sim \text{norm}(0, 1)$   

13     $\tau_l = \frac{1}{a^l} \ln \left( \frac{1}{r_l} \right)$   

14    select  $F_\alpha$  with smallest tentative time  $\tau = \min_{l=1}^L \{\tau_l\}$   

15    generate a random number  $r \sim \text{norm}(0, 1)$   

16    select  $R_\mu \in F_\alpha$  with the smallest index  $\mu$  such that  $\sum_{k=j}^{\mu} a_k \geq r a^\alpha$   

17     $\vec{X} = \vec{X} + \vec{v}_\mu$   

18     $t = t + \tau$ 

```

3.3.4.2.1 Discussion

3.3.4.2.1.1 Performance It can be seen how $L + 1$ random numbers are generated by FFM, so it has better performance than FRM when the number of reactions $M \gg L$ thanks to the smaller number of random number generation. This algorithm is still parallelizable for the families.

3.3.4.2.1.2 Comparison with DM and FRM DM and FRM are special cases of FFM obtained by tuning L and k_l . If $L = 1$ the algorithm is reduced to the DM. If $L = M$ and $k_l = 1$ the algorithm reduces to FRM. Great attention has to be paid to the propensity of the families: if one is much greater than the other the algorithm could choose only that family.

3.4 Next reaction method

The next reaction method NRM improves FRM:

- Avoids recomputing propensities of all reaction after a firing. It recomputes the propensity a_j of R_j only if it actually changes extracting them from a reaction dependency graph G .

3.4. NEXT REACTION METHOD

- Switches to absolute tentative time instead of relative and reuses the time when appropriate. For each simulation step it generates the new time for the reaction firing, while the other are updated and reused, reducing the number of random number used in the simulation.
- it employs efficient data structures to store and retrieve putative firing time of reaction, making the selection of the next reaction fast and efficient.

3.4.1 Absolute tentative time

Let τ_j be the tentative time to the firing of R_j with pdf $p(\tau_j | \text{vec}x, t) = a_j e^{-a_j \tau_j}$. Let $\tau_m = \min_{k=1}^M \tau_j$. The residual $\tau_j - \tau_m$ is transformed for all $j \neq \mu$ to compute the new tentative time for R_j .

3.4.1.1 Distribution of the residual time

$\tau_j - \tau_\mu$ is exponentially distributed with rate a_j : let X be a random variable with an exponential density function:

$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

Where $\lambda > 0$ is a parameter, then, $\forall s > t \geq 0$:

$$\mathbb{P}\{X > s | X > t\} = \mathbb{P}\{X > s - t\}$$

Expanding the left-hand side:

$$\begin{aligned} \mathbb{P}\{X > s | X > t\} &= \frac{\mathbb{P}\{X > s \wedge X > t\}}{\mathbb{P}\{X > t\}} = \frac{\mathbb{P}\{X > s\}}{\mathbb{P}\{X > t\}} = \frac{1 - \mathbb{P}\{X \leq s\}}{1 - \mathbb{P}\{X \leq t\}} = \\ &= \frac{1 - \int_{-\infty}^s f(x) dx}{1 - \int_{-\infty}^t f(x) dx} = \frac{1 - \int_0^s \lambda e^{-\lambda x} dx}{1 - \int_0^t \lambda e^{-\lambda x} dx} = \frac{e^{-\lambda s}}{e^{-\lambda t}} = \\ &= e^{-\lambda(s-t)} \end{aligned}$$

And the right-hand side:

$$\begin{aligned} \mathbb{P}\{X > s - t\} &= 1 - \mathbb{P}\{X \leq s - t\} = 1 - \int_{-\infty}^{s-t} f(x) dx = \\ &= 1 - \int_0^{s-t} \lambda e^{-\lambda x} dx = e^{-\lambda(s-t)} \end{aligned}$$

Obtaining the required equality.

3.4.1.2 Relationship between absolute and relative tentative time

Let t_j the absolute tentative time: the time from the start of the simulation to the firing of R_j . The relationship between the absolute and tentative time is:

$$t_j = t + \tau + j$$

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Where t is the current simulation time. The reaction with the smallest absolute time is the reaction with the smallest relative time because t is fixed. However using it NRM does not need the random number necessary to generate the new tentative times.

3.4.1.3 Computing the absolute time

Let R_μ the reaction with smallest t_μ . After it fires and t is advanced to t_μ , the new times for reactions have to be generated. For R_μ a new tentative time is generated from an exponential distribution $t_\mu^{new} = e^{a_\mu^{new}}$ and the absolute time is updated to:

$$t_\mu^{new} + t_\mu + \tau_\mu^{new}$$

For each R_j with $j \neq \mu$, let a_j^{new} and τ_j^{new} be the new propensity value and new relative time. In the case that R_j does not depend on R_μ and the propensity of the reaction does not change by firing, the difference $\tau_j - \tau_m = t_j - t_\mu$ can be used as the new relative tentative time τ_j^{new} of the reaction, so that the absolute time does not change:

$$t_j^{new} = \tau_j^{new} + t_\mu = t_j - t_\mu + t_\mu = t_j$$

If $R_j \in \text{Depenents}(R_\mu)$ and $j \neq \mu$, the propensity a_j changes to a_j^{new} . A new relative tentative time, an exponential random number with rate a_j^{new} has to be computed.

3.4.1.3.1 Computing the new tentative time Let X be a random variable with exponential density function:

$$f_X(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

Where $\lambda > 0$ is a parameter. Let Y be a random variable such that $Y = cX$, where $c > 0$ is a constant, then the probability density function of Y is:

$$f_Y(x) = \begin{cases} \frac{\lambda}{c} e^{-\frac{\lambda}{c}x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

Let $F_Y(x)$ be the cdf of Y , then:

$$\begin{aligned} f_Y(x) &= \frac{dF_Y(x)}{dx} = \frac{d\mathbb{P}\{Y \leq x\}}{dx} = \frac{d\mathbb{P}\{cX \leq x\}}{dx} = \frac{d\mathbb{P}\{X \leq \frac{x}{c}\}}{dx} = \\ &= \frac{d\left(\int_{-\infty}^{\frac{x}{c}} f_X(s)ds\right)}{dx} \end{aligned}$$

If $x < 0$, then $f_Y(x) = 0$. If $x \geq 0$:

$$\begin{aligned} f_Y(x) &= \frac{d\left(\int_0^{\frac{x}{c}} \lambda e^{-\lambda s} ds\right)}{dx} = \frac{d\left(1 - e^{-\frac{\lambda}{c}x}\right)}{dx} = \\ &= \frac{\lambda}{c} e^{-\frac{\lambda}{c}x} \end{aligned}$$

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This ensures that:

$$\tau_j^{new} = \frac{a_j}{a_j^{new}}(t_j - t_\mu)$$

Is exponentially distributed with rate a_j^{new} as desired, so the new value for the absolute tentative time for R_j is:

$$t_j^{new} = \tau_j^{new} + t_\mu = \frac{a_j}{a_j^{new}}(t_j - t_\mu) + t_\mu$$

3.4.1.4 Conclusion

In conclusion NRM does not generate new random numbers to compute the new times for all the reactions: the old time is reused to compute the new one.

3.4.2 Data structures

To speed up the selection of the minimum t_μ , NRM employs a binary heap to index the absolute putative times t_j of reactions R_j . Each node is a pair (t_j, R_j) in which t_j is a key that prioritize the node. It maintains a partial order between nodes: the parent have a smaller time than its child. The selection of the reaction with smallest time is constant: it is on the top of the heap. The heap has to be updated for each reaction whose time is changed. To do this the node containing the reaction is updated with the new time and is swept up and down to maintaining the order of the heap. This costs $O(\log(M))$.

3.4.3 Algorithm

An implementation of the next reaction method is presented in algorithm 17.

3.4. NEXT REACTION METHOD

Algorithm 17: Next Reaction Method (NRM) ()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$ 
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3  $t = 0$ 
4  $\vec{X} = \vec{x}_0$ 
5 build the reaction dependency graph  $G$ 
6 foreach  $R_j$  do
7   compute  $a_j$ 
8   generate a random number  $r_j \sim \text{norm}(0, 1)$ 
9    $t_j = \frac{1}{a_j} \ln \left( \frac{1}{r_j} \right)$ 
10 build the binary heap  $H$  for  $M$  tentative times  $t_j$ 
11 while  $t < T_{\max}$  do
12   extract the node with smallest  $t_\mu$  and reaction  $R_\mu$  from  $H$ 
13    $t = t_\mu$ 
14    $\vec{X} = \vec{X} + \vec{v}_\mu$ 
15   foreach  $R_j \in \text{Dependents}(R_\mu)$  do
16     compute  $a_j^{new}$ 
17     if  $j \neq \mu$  then
18        $t_j = \frac{a_j}{a_j^{new}} (t_j - t) + t$ 
19     else if  $j = \mu$  then
20       generate a random number  $r \sim \text{norm}(0, 1)$ 
21        $t_\mu = t + \frac{1}{a_\mu^{new}} \ln \frac{1}{r}$ 
22        $a_j = a_j^{new}$ 
23     replace the old time  $t_j$  in  $H$  with the new value  $t_j^{new}$  and maintain the heap  $H$ 

```

3.4.3.1 Discussion

3.4.3.1.1 Time complexity The computation cost of NRM scales as the logarithm of M . For each simulation step, the extraction of the smallest time, advancing the simulation to the new time and updating the state are constant. The update cost in the for dominates the total cost. It iterates over all the dependent reaction to calculate their new times and perform the heap update, for one reaction this costs $O(\log(M))$. Let D be the average number of reaction that are dependent on the reaction firing, then the total cost of update is $O(D \log(M))$. If D is small and is bounded by a constant, then the total cost is $O(\log(M))$. Moreover only one random number is necessary for each simulation step, so the number of random numbers used by NRM is optimal.

3.4.3.1.2 Inactive reaction When a reaction is inactive $a_j = 0$ before firing R_μ and becomes active after the reaction, the new time of R_j will be $t_j^{new} = t_\mu$, which is not possible. A solution for the implementation of this step is to generate a new putative time τ_j^{new} by sampling $e^{a_j^{new}}$ rather than applying the transformation.

3.4.4 Modified next reaction method

The modified next reaction method MNRM is a variant of NRM where the firing time of reaction are represented as independent Poisson processes with rates given by their integrated propensities.

3.4.4.1 Poisson process

Let $Y(t), t \geq 0$ be a process that counts the number of events by time t . $Y(t)$ is a Poisson process with rate $\lambda > 0$ if:

- $Y(0) = 0$.
- $Y(t)$ has the stationary increment property:
 $\forall [t, t + \Delta t], Y(t) - Y(t + \Delta t)$ has the same distribution as $Y(\Delta t)$.
- $Y(t)$ has the independent increment prop-

erty: $\forall [t, t + \Delta t] \wedge [t', t' + \Delta t']$ such that $[t, t + \Delta t] \cap [t', t' + \Delta t'] = \emptyset$, $Y(\Delta t)$ is independent of $Y(\Delta t')$.

- The probability of observing one event in the infinitesimal $[t, t + dt]$ is $\mathbb{P}\{Y(t + dt) - Y(t) = 1\} = \lambda dt + o(dt)$

Now let $Y(t)$ be a Poisson process with rate λ , then:

- The distribution $Y(t), t \geq 0$ is a Poisson distribution $poi(\lambda t)$.
- The time to the next event of the Poisson process is an exponential distribution $exp(\lambda)$.

3.4.4.1.1 $Y(t)$ is a Poisson distribution To prove the first claim let $\mathbb{P}\{Y(t) = k\}$ be the probability that there are k events in $[0, t]$. Suppose that this is divided into intervals $[\frac{(i-1)t}{n}, \frac{it}{n}]$ of length $\frac{t}{n}$ such that there is at most one event in each subinterval. The number of events in $[0, t]$ is the sum of the events observed in the subintervals. By definition of $Y(t)$, the probability of observing an event in the subinterval is $\frac{\lambda t}{n}$. The probability $\mathbb{P}\{Y(t) = k\}$ follows a binomial distribution with success probability $\frac{\lambda t}{n}$:

$$\mathbb{P}\{Y(t) = k\} = \binom{n}{k} \left(\frac{\lambda t}{n}\right)^k \left(1 - \frac{\lambda t}{n}\right)^{n-k} = \frac{n!}{k!(n-k)!} \left(\frac{\lambda t}{n}\right)^k \left(1 - \frac{\lambda t}{n}\right)^{n-k}$$

Expanding the factorial and taking the limit $n \rightarrow \infty$:

$$\begin{aligned} \mathbb{P}\{Y(t) = k\} &= \lim_{n \rightarrow \infty} \frac{n}{n} \frac{n-1}{n} \dots \frac{n-k-1}{n} \left(1 - \frac{\lambda t}{n}\right)^{-k} \frac{(\lambda t)^k}{k!} \left(1 - \frac{\lambda t}{n}\right)^n = \\ &= \frac{(\lambda t)^k e^{-\lambda t}}{k!} \end{aligned}$$

Considering that $\lim_{n \rightarrow \infty} \left(1 - \frac{\lambda t}{n}\right)^n = e^{-\lambda t}$. In conclusion then the probability $\mathbb{P}\{Y(t) = k\}$ denotes a Poisson distribution $poi(\lambda t)$.

3.4.4.1.2 The time to the next event is an exponential distribution Let T be the time to the next event of the Poisson process $Y(t)$. By definition of the Poisson process, it only needs to consider the time to the first event after 0. Let F_T be the cdf of T :

$$F_T(t) = \mathbb{P}\{T \leq t\} = \mathbb{P}\{Y(t) \geq 1\} = 1 - \mathbb{P}\{Y(t) = 0\} = 1 - \frac{(\lambda t)^0 e^{-\lambda t}}{0!} = 1 - e^{-\lambda t}$$

Considering that $\mathbb{P}\{Y(t) \geq 1\} = \mathbb{P}\{T \leq t\}$. This shows that the time T to the next event follows an exponential distribution $\exp(\lambda)$.

3.4.4.2 Unit Poisson process

The Poisson process with rate 1 is called a unit Poisson process. If $Y(t)$ denotes a unit Poisson process, then $T(\lambda t)$ is a Poisson process with rate λ .

3.4.4.3 Random time change representation

Let $C_j(t)$ be the number of times that R_j fires up to t . $C(t)$ satisfies the conditions of the Poisson process. The probability that R_k fires in $[t, t + dt]$ by definition of a_j is:

$$\mathbb{P}\{C_j(t + dt) - C_j(t) = 1 | X(s), s \leq t\} = a_j(X(t))dt + o(dt)$$

$C_j(t)$ denotes a Poisson process with rate $a_j(X(T))$. Let $Y_j(t)$ be an independent unit Poisson process. $C_j(t)$ is represented in MNRN in term of $Y_j(t)$. It can be noted how:

$$C_j(t) = Y_j \left(\int_0^t a_j(X(s))ds \right)$$

Or the random time change RTC representation.

3.4.4.4 Internal time

The internal time I_j of Y_j associated with R_j is:

$$I_j(t) = \int_0^t a_j(X(s))ds$$

$I_j(t)$ given t shows the amount of time that Y_j passed before it expires due to the firing of R_j . Each reaction can be seen as carrying its own internal clock, with a rate given by the integration of the propensity. There are $M + 1$ time frames in which the first is the physical time t and the last M are for M Poisson processes Y_j . The internal time is a dimensionless quantity.

3.4.4.4.1 Computing the tentative time Let t be the current time, the system state is $X(t) = \vec{x}$. The propensity a_j and the internal time is $T_j = I_j(t)$. The internal time at time $t = 0$ is $I_j(0) = 0$. Let P_j be the next internal event time of Y_j with corresponding physical time $t_j > t$, $P_j = I_j(t)$. The relationship between T_j and P_j is:

$$P_j = I_j(t_j) = I_j(t) + a_j(t_j - t) = T_j + a_j\tau_j$$

Where $\tau_j = t_j - t$ is the relative time to the firing of R_j . The amount of internal time to the firing is $a_j\tau_j$. Because Y_j is a unit Poisson process, the time to the next firing follows a distribution $\exp(1)$: the amount $P_j - T_j$ is an exponentially distributed random number with rate 1. If the current internal time T_j and the next internal time P_j are tracked, the tentative time to the firing, given that no other reaction fires before is:

$$\tau_i = \frac{P_j - T_j}{a_j}$$

3.4. NEXT REACTION METHOD

The selection with minimum τ_μ will be selected to fire.

3.4.4.4.2 Updating the firing time Suppose that the reaction R_μ fires at time $t_\mu = t + \tau_\mu$. The next internal event time P_j of Y_μ must be generated because it expired, the new time is computed as:

$$\tau_i = \frac{P_j - T_j}{a_j}$$

For reaction R_j , with $j \neq \mu$, the updated internal time of process Y_j at time $t + \tau_\mu$ is:

$$I_j(t + \tau_\mu) = I_j(t) + a_j \tau_\mu$$

Let a_j^{new} be the new propensity and τ_j^{new} be the new tentative time to firing R_j after the firing of R_μ . $a_j^{new} \tau_j^{new}$ is the remaining amount of internal time to the next firing of Y_j . Because the processes are independent, the next internal event time P_j of Y_j does not change:

$$P_j = I_j(t + \tau_\mu) + a_j^{new} \tau_j^{new} = I_j(t) + a_j \tau_\mu + a_j^{new} \tau_j^{new}$$

Comparing it with the other computation of P_j :

$$\tau_j^{new} = \frac{a_j}{a_j^{new}} (\tau_j - \tau_\mu) = \frac{a_j}{a_j^{new}} (t_j - t_\mu)$$

Then the absolute time to the next firing of R_j :

$$t_j^{new} = t_\mu + \tau_j^{new} = \frac{a_j}{a_j^{new}} (\tau_j - \tau_\mu) + t_\mu$$

Which is the transformation used by NRM: the selection of the next reaction firing is exact.

3.4.4.5 Algorithm

An implementation of MNRM is outlined in algorithm 18.

3.5. REJECTION BASED STOCHASTIC SIMULATION ALGORITHM

Algorithm 18: Modified Next Reaction Method (MNRM)()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 build the reaction dependency graph  $G$   

6 foreach  $R_j$  do  

7    $T_j = 0$   

8   generate a random number  $r_j \sim \text{norm}(0, 1)$   

9    $P_j = \ln \frac{1}{r_j}$   

10  compute  $a_j$   

11 while  $t < T_{\max}$  do  

12   foreach  $R_j$  do  

13      $\tau_j = \frac{1}{a_j}(P_j - T_j)$   

14   select  $R_\mu$  with the smallest time  $\tau = \min_{j=1}^M \{\tau_j\}$   

15    $\vec{X} = \vec{X} + \vec{v}_\mu$   

16    $t = t + \tau$   

17   foreach  $R_j$  do  

18      $T_j = T_j + a_j \tau$   

19     if  $j = \mu$  then  

20       generate a random number  $r \sim \text{norm}(0, 1)$   

21        $P_\mu = P_\mu + \ln \frac{1}{r}$   

22     if  $R_j \in \text{Dependents}(R_\mu)$  then  

23       compute new  $a_j$ 

```

3.4.4.5.1 Discussion The simulation of MNRM is equivalent to NRM. MNRM explicitly works with internal time arising from the RTC representation, while NRM works with physical time. This makes MNRM more flexible to handle complex propensity function and helps make a smooth connection between exact stochastic simulation and the class of Poisson approximation, like the τ -leaping algorithm.

3.5 Rejection Based stochastic simulation algorithm

The rejection based stochastic simulation algorithm or RSSA is an exact simulation algorithm that tries to reduce the number of propensity updates during the simulation. Each simulation iteration selects a R_μ with probability $\frac{a_\mu}{a_0}$ and its firing time is exponentially distributed according to a_0 . The selection of the next reaction firing in RSSA is an acceptance-rejection sampling technique that allows to skip the propensity updates in most of the iterations. They are recomputed only when necessary. Because of this it is useful for reaction in which propensities are complex.

3.5.1 Fluctuation interval

For each species S_i RSSA abstracts its exact population $X_i(t)$ with a fluctuation interval $[\underline{X}_i, \bar{X}_i]$. The interval can be chosen arbitrarily around the current population without affecting the correctness of the algorithm. The fluctuation interval can be defined as:

$$[\underline{X}_i, \bar{X}_i] = [(1 - \delta_i)X_i(t), (1 + \delta_i)X_i(t)]$$

Where δ_i is the parameter called fluctuation rate. A good choice for real biological model is from 10 to 20% of current population of species. Considering abstraction interpretation terminology, $X(t)$ is called the concrete state, while $[\underline{X}, \bar{X}]$ is the abstract state. For each species holds:

$$\underline{X} \leq X(t) \leq \bar{X}$$

3.5.2 Abstract propensity value

For each R_j an abstract propensity value $[\underline{a}_j, \bar{a}_j]$ is computed, this is an interval encompassing all its possible values, including the exact one $a_j(X(t))$. The bounds are derived by minimizing and maximizing a_j over the fluctuation interval. For the standard mass action or Michaelis-Menten kinetics, a_j is a monotonic function of the state X , so that $\underline{a}_j = a_j(\underline{X})$ and $\bar{a}_j = a_j(\bar{X})$. If it is non-monotonic, a numerical optimization technique or interval analysis can be applied to recover the bounds. The exact bounds are not needed as the tight bounds of a_j over the fluctuation interval are sufficient.

3.5.3 Selection of the next reaction

The selection of the next reaction has two steps:

- Simulation of the abstract model.
- Acceptance of the candidate reaction.

3.5.3.1 Simulation of the abstract model

In the first step RSSA simulates the abstract model assigning to each $R_j \frac{\bar{a}_j}{\bar{a}_0}$, where $\bar{a}_0 = \sum_{j=1}^M \bar{a}_j$. R_μ is randomly selected with probability $\frac{\bar{a}_\mu}{\bar{a}_0}$ as a candidate. The realization of R_μ is performed accumulating propensity upper bounds until the smallest μ is selected such that:

$$\sum_{j=1}^{\mu} \bar{a}_j \geq r_1 \bar{a}_0$$

Where $r_1 \sim \text{norm}(0, 1)$.

3.5.3.2 Acceptance of the abstract model

In the second step RSSA checks whether R_μ is accepted to occur in the concrete model through a rejection test with success probability $\frac{a_\mu}{\bar{a}_\mu}$. Since the exact value of the propensity is not known, a random number $r_2 \sim \text{norm}(0, 1)$ is drawn to check whether:

$$r_2 \leq \frac{a_\mu}{\bar{a}_\mu}$$

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If this succeeds R_μ is accepted because $r_2 \leq \frac{a_\mu}{\bar{a}_\mu} \leq \frac{a_\mu}{\hat{a}_\mu}$. When this fails a_μ is computed and r_2 is tested against $\frac{a_\mu}{\hat{a}_\mu}$. This happens infrequently when $\frac{a_\mu}{\hat{a}_\mu}$ is close to 1. If R_μ is accepted the firing time is computed, otherwise a new reaction is selected and tested again.

3.5.4 Advancement of the simulation

To remain exact RSSA has to advance the simulation at every attempt of rejection by an exponentially distributed variable with parameter \bar{a}_0 . Assuming $k-1$ reactions and following the acceptance, the simulation has to advance by a quantity equal to the sum of k exponential random numbers:

$$\frac{1}{\bar{a}_0} \ln \frac{1}{u_1} + \frac{1}{\bar{a}_0} \ln \frac{1}{u_2} + \cdots + \frac{1}{\bar{a}_0} \ln \frac{1}{u_k}$$

Where $u_i \sim \text{norm}(0, 1)$ are independent and identically distributed random numbers. This sum is the Erlang distribution $\text{erlang}(k, \bar{a}_0)$.

3.5.5 Exactness of RSSA

For each simulation iteration of RSSA, R_μ is selected to fire with probability $\frac{a_\mu}{a_0}$ and its firing time τ follows an exponential distribution with rate a_0 . Let $\mathbb{P}\{R_\mu\}$ be the probability that R_μ is selected and accepted to fire in a single attempt. This can be expressed as the product of the probability of being selected and being accepted:

$$\mathbb{P}\{R_\mu\} = \frac{\bar{a}_\mu}{\bar{a}_0} \frac{a_\mu}{\bar{a}_0} = \frac{a_\mu}{\bar{a}_0}$$

Let $\mathbb{P}\{R\}$ be the probability that some reaction is accepted in a single attempt, this is:

$$\mathbb{P}\{R\} = \frac{\sum_{j=1}^M a_j}{\bar{a}_0} = \frac{a_0}{\bar{a}_0}$$

R_μ being accepted after any number of rejections is a conditional probability of accepting R_μ knowing some reaction is accepted:

$$\mathbb{P}\{R_\mu|R\} = \frac{\frac{a_\mu}{\bar{a}_0}}{\frac{a_0}{\bar{a}_0}} = \frac{a_\mu}{a_0}$$

Demonstrating that the reaction is selected with the correct probability. Now let F_V be the cdf and f_V the pdf of V . Let k be the random variable for the number of attempts performed before accepting R_μ . k is geometrically distributed with success probability $\mathbb{P}\{R\}$. Let τ be a random variable corresponding to the simulation time advancement due to the firing of R_μ . Let $\mathbb{P}(\tau \leq x)$ be the probability that $\tau \leq x$ given a reaction is accepted after some trials, the pdf of τ :

$$\begin{aligned}
 f_\tau(x) &= \frac{\partial}{\partial x} \mathbb{P}\{\tau \leq x\} = \\
 &= \frac{\partial}{\partial x} \sum_{k_0=1}^{\infty} \mathbb{P}\{\tau \leq x | k = k_0\} \mathbb{P}\{k = k_0\} = \\
 &= \frac{\partial}{\partial x} \sum_{k_0=1}^{\infty} F_{erlang(k_0, \bar{a}_0)}(x) \frac{a_0}{\bar{a}_0} \left(1 - \frac{a_0}{\bar{a}_0}\right)^{k_0-1} = \\
 &= \sum_{k_0=1}^{\infty} \frac{\partial}{\partial x} F_{erlang(k_0, \bar{a}_0)}(x) \frac{a_0}{\bar{a}_0} \left(1 - \frac{a_0}{\bar{a}_0}\right)^{k_0-1} = \\
 &= \sum_{k_0=1}^{\infty} f_{erlang(k_0, \bar{a}_0)}(x) \frac{a_0}{\bar{a}_0} \left(1 - \frac{a_0}{\bar{a}_0}\right)^{k_0-1} = \\
 &= \sum_{k_0=1}^{\infty} \frac{\bar{a}_0^{k_0} x^{k_0-1} e^{-\bar{a}_0 x}}{(k_0-1)!} \frac{a_0}{\bar{a}_0} \left(\frac{\bar{a}_0 - a_0}{\bar{a}_0}\right)^{k_0-1} = \\
 &= a_0 e^{-\bar{a}_0 x} \sum_{k_0=1}^{\infty} \frac{(\bar{a}_0 - a_0)^{k_0-1} x^{k_0-1}}{(k_0-1)!} = \\
 &= a_0 e^{-\bar{a}_0 x} e^{x(\bar{a}_0 - a_0)} = a_0 e^{-a_0 x}
 \end{aligned}$$

Noting that:

- Partitioning $\mathbb{P}(\tau < x)$ according to k is done because for a fixed k , τ is an Erlang distribution with parameters k and \bar{a}_0 .
- Applying the closed form of the pdf of Erlang.
- $e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!}$.

This shows how the firing time τ follows an exponential distribution $\exp(a_0)$.

3.5.5.1 Bounds on the acceptance probability

The acceptance probability of a single attempt $\mathbb{P}\{R\}$ is bounded by:

$$\frac{a_0}{\bar{a}_0} \leq \mathbb{P}\{R\} = \frac{a_0}{\bar{a}_0} \leq 1$$

Tighter lower or upper bounds yield a better acceptance probability: if $[\underline{X}, \bar{X}]$ is reduced to the concrete state $X(t)$, the acceptance probability is 1:

$$\underline{a_j} = \bar{a_j} = a_j$$

And RSSA is reduced to DM.

3.5.6 Evolution of the state

After firing $X(t)$ is updated and RSSA checks whether the new concrete state is compatible with the abstract state: $\underline{X_i} \leq X_i(t) \leq \bar{X_i}$ holds for each species. This is often the case as a reaction only

affects a few molecules. When this is true RSSA does not recompute the abstract propensities: the inequality $\underline{a}_j \leq a_j \leq \bar{a}_j$ still holds for all reaction and the next reaction step can be performed. If $X(t)$ falls outside the abstract state the abstract propensities have to be updated by redefining a new abstract state around the new concrete one and deriving the corresponding propensities. This operation can be made cheaper by observing that only the reaction affected by the species for which a new fluctuation interval has been redefined require an update of the propensity bounds. This are determined by a species-reaction RS dependency graph.

3.5.6.1 Species-Reaction dependency graph

Let \mathcal{S} and \mathcal{R} be the set of species and reactions in the biochemical network. The species-reaction SR dependency graph is the direct bipartite graph $\mathcal{G}(V, E)$ having:

$$\begin{aligned} V &= \mathcal{S} \cup \mathcal{R} \\ E &= \{(s, r) \in \mathcal{S} \times \mathcal{R} | s \in \text{Reactants}(r)\} \cup \{(r, s) \in \mathcal{R} \times \mathcal{S} | s \in \text{Products}(r)\} \end{aligned}$$

This is a bipartite graph that shows the dependency of reactions on species. This allows RSSA to decide which reaction should recompute their propensity bounds. For a species S_i if its population moves out of the fluctuation interval RSSA recomputes propensity bounds of a reaction R_j if there is a directed edge from S_i to R_j in SR . The number of reaction that needs to recompute propensity bounds is equal to the out-degree of S_i . The reactions that have to recompute the propensity bounds if $X_i(t) \notin [\underline{X}_i, \bar{X}_i]$ are defined in term of the SR as:

$$\text{ReactionAffectedBy}(S_i) = \{R_j | \exists (S_i, R_j) \in \mathcal{G}\}$$

3.5.7 Algorithm

An implementation of RSSA is outlined in algorithm 19.

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Algorithm 19: Rejection-Based SSA (RSSA)()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$ 
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3  $t = 0$ 
4  $\vec{X} = \vec{x}_0$ 
5 build the species reaction SR dependency graph  $\mathcal{G}$ 
6 foreach  $S_i \in Species$  do
7   define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
8  $\bar{a}_0 = 0$ 
9 foreach  $R_j \in Reactions$  do
10  compute  $\bar{a}_j$  and  $\underline{a}_j$ 
11   $\bar{a}_0 = \bar{a}_0 + \bar{a}_j$ 
12 while  $t < T_{\max}$  do
13   repeat
14      $u = 1$ 
15     accepted = false
16     repeat
17       generate three random numbers  $r_1, r_2, r_3 \sim norm(0, 1)$ 
18       select  $R_\mu$  with minimum  $\mu$  such that  $\sum_{j=1}^{\mu} \bar{a}_j \geq r_1 \bar{a}_0$ 
19       if  $r_2 \leq \frac{\underline{a}_\mu}{\bar{a}_\mu}$  then
20         accepted = true
21       else
22         evaluate  $a_\mu$  with state  $X$ 
23         if  $r_2 \leq \frac{\underline{a}_\mu}{a_\mu}$  then
24           accepted = true
25        $u = u \cdot r_3$ 
26     until accepted
27      $\tau = \frac{1}{\bar{a}_0} \ln(u)$ 
28      $\vec{X} = \vec{X} + \vec{v}_\mu$ 
29      $t = t + \tau$ 
30   until  $\exists(X_i \notin [X_i, \bar{X}_i])$ 
31   foreach  $X \notin [X_i, \bar{X}_i]$  do
32     define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
33     foreach  $R_j \in ReactionsAffectedBy(S_i)$  do
34       compute new propensity bounds  $\bar{a}_j$  and  $\underline{a}_i$ 
35       update  $\bar{a}_0$ 

```

3.5.7.1 Discussion

3.5.7.1.1 Time complexity The time complexity is composed of the cost to realize a candidate reaction and the number of rejection tests. RSSA accumulates propensity upper bounds linearly until it finds a candidate reaction: selecting the candidate is $O(M)$. Let $\alpha = \frac{\bar{a}_0}{\bar{a}_i}$ be the average number of times the search is performed until a candidate is accepted: the cost for the selection of firing is $O(\alpha M)$. This cost is compensated by a huge reaction in propensity updates: let T_{DM}^{update} be the cost for propensity updates in DM. In RSSA is $\frac{T_{DM}^{update}}{\beta}$, where β is the average number of skipped updates and is the average frequency of $X(t) \in [\underline{X}, \bar{X}]$, providing a significant improvement for the simulation performance.

3.5.8 Simultaneous RSSA

Simultaneous RSSA SRSSA is a variant of RSSA that generates multiple independent trajectories in a simulation run. The propensity bounds in SRSSA are computed once and shared across the simulations, reducing the memory requirements to store the propensity bounds. The recomputing is performed collectively in a single operation which reduces the total number of propensity updates and improves the simulation performance.

3.5.8.1 Global fluctuation interval

Let K be the number of trajectories and X^r the system state of the r -th realization with $r = 1, \dots, K$. Let a_j^r the propensity of reaction R_j in the r -th realization. A lower and upper bound for each R_j such that $\underline{a}_j \leq a_j^r \leq \bar{a}_j \forall r = 1, \dots, K$ and uses these for all K realization. It stores only M propensity bounds, which are derived by first defining a global fluctuation interval $[\underline{X}, \bar{X}]$ which bounds all possible population in all K states X^r . Then a_j is minimized or maximized a_j on the global interval, which can be defined as $X_i^{\min} = \min(X_i^1, \dots, X_i^K)$ and $X_i^{\max} = \max(X_i^1, \dots, X_i^K)$ respectively to be the minimum and maximum of species S_i in all K states. Then the population interval:

$$[\underline{X}_i, \bar{X}_i] = [(1 - \delta_i)X_i^{\min}, (1 + \delta_i)X_i^{\max}]$$

Will bound al population S_i in K states, where δ_i is the fluctuation rate of the species. The new global population intervals are redefined only when all K trajectories are stopped.

3.5.8.2 Algorithm

An implementation of SRSSA is outlined in algorithm 20.

Algorithm 20: Simultaneous RSSA (SRSSA) ()

- 1 **Input:** a biochemical reaction network of M reactions in which each reaction R_j , $j = 1, \dots, M$ is accompanied with the state change vector \vec{v}_j and the propensity a_j , the initial state \vec{x}_0 at time 0 and the simulation ending time T_{\max} and the number of generated trajectories K
- 2 **Output:** K independent trajectory of the biochemical reaction network, which is a collection of states $X^r(t)$ for time $0 \leq t \leq T_{\max}$

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```

1 foreach  $Trajectory \in K$  do
2    $t^r = 0$ 
3    $\vec{X}^r = \vec{x}_0$ 
4   build the species reaction SR dependency graph  $\mathcal{G}$ 
5   foreach  $S_i \in Species$  do
6     define a new  $[\underline{X}_i, \overline{X}_i]$  around  $X_i$ , such that  $\underline{X}_i \leq X_i^1, \dots, X_i^K \leq \overline{X}_i$ 
7    $\overline{a}_0 = 0$ 
8   foreach  $R_j \in Reactions$  do
9     compute  $\overline{a}_j$  and  $\underline{a}_j$ 
10     $\overline{a}_0 = \overline{a}_0 + \overline{a}_j$ 
11  repeat
12     $UpdateSpeciesSet = \emptyset$ 
13    foreach  $r = 1 \rightarrow K$  do
14      repeat
15         $u = 1$ 
16        accepted = false
17        repeat
18          generate three random numbers  $r_1, r_2, r_3 \sim norm(0, 1)$ 
19          select  $R_\mu$  with minimum  $\mu$  such that  $\sum_{j=1}^\mu \overline{a}_j \geq r_1 \overline{a}_0$ 
20          if  $r_2 \leq \frac{a_\mu}{\overline{a}_\mu}$  then
21            accepted = true
22          else
23            evaluate  $a_\mu^r$  with state  $X^r$ 
24            if  $r_2 \leq \frac{a_\mu}{\overline{a}_\mu}$  then
25              accepted = true
26             $u = u \cdot r_3$ 
27            until accepted
28             $\tau^r = \frac{1}{a_0} \ln(u)$ 
29             $\vec{X}^r = \vec{X}^r + \vec{v}_\mu$ 
30             $t^r = t^r + \tau^r$ 
31        until  $\exists(X_i^r \notin [\underline{X}_i, \overline{X}_i]) \vee t^r \geq T_{max}$ 
32        foreach  $S_i$  where  $X_i^r \notin [\underline{X}_i, \overline{X}_i]$  do
33           $UpdateSpeciesSet = UpdateSpeciesSet \cup \{S_i\}$ 
34      foreach  $S_i \in UpdateSpeciesSet$  do
35        define a new  $[\underline{X}_i, \overline{X}_i]$  such that  $\underline{X}_i \leq X_i^1, \dots, X_i^K \leq \overline{X}_i$ 
36        foreach  $R_j \in ReactionsAffectedBy(S_i)$  do
37          compute new propensity bounds  $\overline{a}_j$  and  $\underline{a}_i$ 
38          update  $\overline{a}_0$ 
39  until  $t^r \geq T_{max} \forall r = 1, \dots, K$ 

```

3.5.9 Improvements for RSSA

The search for a candidate reaction in RSSA is linear and becomes a computational bottleneck for large reaction networks.

3.5.9.1 RSSA with tree-based search

The tree-based search can be used to reduce the time complexity of the search for the next reaction to logarithmic time. The tree stores the propensity upper bounds in the RSSA case: the search time for the candidate reaction is $O(\log M)$ and a tree updated is performed in $O(\log M)$. The time complexity of the algorithm is $O(\log M)$.

3.5.9.1.1 Algorithm An implementation of RSSA with tree-based search can be found in algorithm 21.

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Algorithm 21: Rejection-Based SSA with Tree-based search()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$   

2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$   

3  $t = 0$   

4  $\vec{X} = \vec{x}_0$   

5 build the species reaction SR dependency graph  $\mathcal{G}$   

6 foreach  $S_i \in Species$  do  

7   define a new  $[X_i, \bar{X}_i]$  around  $X_i$   

8  $\bar{a}_0 = 0$   

9 foreach  $R_j \in Reactions$  do  

10  compute  $\bar{a}_j$  and  $\underline{a}_j$   

11   $\bar{a}_0 = \bar{a}_0 + \bar{a}_j$   

12 build TREE structure for  $M$  propensity upper bounds  $\bar{a}_j$  by build_tree  

13 while  $t < T_{\max}$  do  

14   repeat  

15      $u = 1$   

16     accepted = false  

17     repeat  

18       generate three random numbers  $r_1, r_2, r_3 \sim norm(0, 1)$   

19       select  $R_\mu$  by search_tree  

20       if  $r_2 \leq \frac{\underline{a}_\mu}{\bar{a}_\mu}$  then  

21         accepted = true  

22       else  

23         evaluate  $a_\mu$  with state  $X$   

24         if  $r_2 \leq \frac{\underline{a}_\mu}{\bar{a}_\mu}$  then  

25           accepted = true  

26        $u = u \cdot r_3$   

27     until accepted  

28      $\tau = \frac{1}{\bar{a}_0} \ln(u)$   

29      $\vec{X} = \vec{X} + \vec{v}_\mu$   

30      $t = t + \tau$   

31   until  $\exists (X_i \notin [X_i, \bar{X}_i])$   

32   foreach  $X \notin [X_i, \bar{X}_i]$  do  

33     define a new  $[X_i, \bar{X}_i]$  around  $X_i$   

34     foreach  $R_j \in ReactionsAffectedBy(S_i)$  do  

35       compute new propensity bounds  $\bar{a}_j$  and  $\underline{a}_i$   

36       update the Tree bu algorithm update_tree  

37       update  $\bar{a}_0$ 

```

3.5.9.2 RSSA with composition-rejection search

RSSA with composition-rejection search RSSA-CR employs composition-rejection search. The reaction are partitioned into L groups using the propensity bounds. R_j is put into G_l if $2^{u_l-1} \leq \bar{a}_j < 2^{u_l}$ where $u_l = \lceil \log_2(\bar{a}_j) \rceil$. Let $p_l = \sum_{R_j \in G_l} \bar{a}_j$ and $p_o = \sum_{l=1}^L p_l = \sum_{j=1}^M \bar{a}_j = \bar{a}_0$.

3.5.9.2.1 Selection of the next reaction The selection of the next reaction is a two step process:

- Selection of the group.
- Selection of a reaction.

3.5.9.2.1.1 Selection of a group A group G_α is selected with probability $\frac{p_\alpha}{p_0}$ by linearly accumulating p_l until a minimum α such that $\sum_{l=1}^{\alpha} p_l \geq r_1 p_0$ is found, where $r_0 \sim \text{norm}(0, 1)$.

3.5.9.2.1.2 Selection of a reaction The selection of R_μ has two consecutive acceptance-rejection tests: the first randomly selects $R_\mu \in G_\alpha$ and accepts it with probability $\frac{\bar{a}_\mu}{2^{\mu\alpha}}$. This is repeated until R_μ is accepted. Then a second test with acceptance probability $\frac{a_\mu}{\bar{a}_\mu}$ is performed. If the test fails both R_μ and G_α are rejected.

3.5.9.2.2 Firing time The firing time is generated by sampling $\text{erlang}(k, p_0)$, but the number of trials k counts only the second rejection test.

3.5.9.2.3 Algorithm An implementation of RSSA with composition-rejection search can be found in algorithm 22.

Algorithm 22: Rejection-Based SSA (RSSA) ()

- 1 **Input:** a biochemical reaction network of M reactions in which each reaction R_j , $j = 1, \dots, M$ is accompanied with the state change vector \vec{v}_j and the propensity a_j , the initial state \vec{x}_0 at time 0 and the simulation ending time T_{\max}
 - 2 **Output:** a trajectory of the biochemical reaction network, which is a collection of states $X(t)$ for time $0 \leq t \leq T_{\max}$
-

```

1  $t = 0$ 
2  $\vec{X} = \vec{x}_0$ 
3 build the species reaction SR dependency graph  $\mathcal{G}$ 
4 foreach  $S_i \in Species$  do
5   define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
6  $\bar{a}_0 = 0$ 
7 foreach  $R_j \in Reactions$  do
8   compute  $\bar{a}_j$  and  $a_j$ 
9    $\bar{a}_0 = \bar{a}_0 + \bar{a}_j$ 

10 group  $M$  reaction into  $L$  groups so that  $R_j \in G_l$  if  $2^{u_l-1} \leq \bar{a}_j < 2^{u_l}$ 
11  $p_0 = \sum_{l=1}^K p_l$ 
12 while  $t < T_{\max}$  do
13   repeat
14      $u = 1$ 
15     accepted = false
16     repeat
17       generate three random numbers  $r_1 \sim norm(0, 1)$ 
18       select minimum group index  $\alpha$  such that  $\sum_{l=1}^{\alpha} p_l \geq r_1 p_0$ 
19       repeat
20         generate a random number  $r_2 \sim norm(0, 1)$ 
21          $\mu = [r_2 \cdot |G_{\alpha}|]$ 
22          $r_2 = r_2 |G_{\alpha}| - \mu$ 
23       until  $r_2 = r_2 |G_{\alpha}| - \mu$ 
24       generate two random numbers  $r_3, r_4 \sim norm(0, 1)$ 
25       if  $r_3 \leq \frac{a_{\mu}}{\bar{a}_{\mu}}$  then
26         accepted = true
27       else
28         evaluate  $a_{\mu}$  with state  $X$ 
29         if  $r_3 \leq \frac{a_{\mu}}{\bar{a}_{\mu}}$  then
30           accepted = true
31        $u = u \cdot r_4$ 
32     until accepted
33      $\tau = \frac{1}{p_0} \ln(u)$ 
34      $\vec{X} = \vec{X} + \vec{v}_{\mu}$ 
35      $t = t + \tau$ 
36   until  $\exists(X_i \notin [X_i, \bar{X}_i])$ 
37   foreach  $X \notin [X_i, \bar{X}_i]$  do
38     define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
39     foreach  $R_j \in ReactionsAffectedBy(S_i)$  do
40       compute new propensity bounds  $\bar{a}_j$  and  $a_i$ 
41       update  $G_l$  with its  $p_l$  and sum  $p_0$ 

```

3.5.9.2.4 Discussion

3.5.9.2.4.1 Time complexity The time complexity consist of the cost of selecting the group in $O(L)$ and the average number of times that the validation test is performed to accept a reaction is $\alpha = \frac{2\bar{a}_\mu}{a_\mu}$, which is dependent on the ratio of the propensity bounds which can be tuned through the fluctuation interval. The total computational cost for the selection of a reaction is $O(L)$.

3.5.9.3 RSSA with table-lookup search

The alias table lookup search is a constant time search but it requires an expensive pre-processing step to build the lookup tables. Any discrete probability distribution over M probability values can be expressed as an equi-probable mixture of M two-points distribution. The M probabilities are $\frac{\bar{a}_j}{\bar{a}_0}$. The setup requires to build two tables implemented as arrays of size M in which the first, the cut-off table Q , stores the first values of the two point mixture and the second, the alias table A , contains the alias to the second part.

3.5.9.3.1 Building the tables When building the tables the objective is to transform the M probabilities into a square histogram. The probabilities greater than average are stored in the *Greater* set and the smaller in the *Smaller* one. For each loop an element of *Greater* and an element of *Smaller* are selected. The element from *Greater* transfer a part of its value to the smaller one from *Smaller* to make it average. This step implies that for $l \in \text{Smaller}$ such that $Q_l < 1$ there is no alias. This is repeated until all elements in *Smaller* are reprocessed. To show that it will never reach a deadlock consider the invariant of the while loop, the sum of element in *Greater* and *Smaller* is:

$$\text{Total} = \sum_{j=1}^M Q_j = M$$

The average value will be 1. For each loop $l \in \text{Smaller}$ with value Q_l is removed and value Q_k of $k \in \text{Greater}$ is reduced by $1 - Q_l$. The total sum is reduced by 1, so the loss after the i -th loop is:

$$\text{Loss} = \sum_{k=1}^i 1 = i$$

The total number of elements in the sets is $M - i$: in each loop one element from *Smaller* is removed. The average value of elements in the sets after the i -th loop is:

$$\frac{\text{Total} - \text{Loss}}{M - i} = 1$$

For each loop, if *Smaller* is not empty there is at least one element in *Greater*, proving the claim. This procedure is outlined in algorithm 23.

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Algorithm 23: build_alias_table()

```

1 Input:  $M$  probabilities  $\frac{\bar{a}_j}{\bar{a}_0}$ 
2 Output: alias table  $A$  with size  $M$  storing reaction indices and cut-off table  $Q$  with size  $M$ 
   storing cut-off probabilities
3 foreach  $j = 1 \rightarrow M$  do
4    $Q_j = M \frac{\bar{a}_j}{\bar{a}_0}$ 
5    $Greater = \emptyset$ 
6    $Smaller = \emptyset$ 
7   foreach  $j = 1 \rightarrow M$  do
8     if  $Q_j \geq 1$  then
9       add  $j$  to  $Greater$ 
10    else
11      add  $j$  to  $Smaller$ 
12 while  $Greater \neq \emptyset \wedge Smaller \neq \emptyset$  do
13   take  $k \in Greater$  and  $l \in Smaller$ 
14    $A_l = k$ 
15   remove  $l$  from  $Smaller$ 
16    $Q_k = Q_k - (1 - Q_l)$ 
17   if  $Q_k < 1$  then
18     move  $k$  from  $Greater$  to  $Smaller$ 

```

3.5.9.3.2 Search for the candidate reaction The search considers a random number $r \sim norm(0, 1)$ as the parameter. First a random index $\mu = [Mr]$ is computed, where $[-]$ is the truncation operator. r is rescaled and compared against Q_μ the probability cut-off. If $r < Q_\mu$ μ is returned, otherwise the reaction index in A_μ is returned. This procedure is outlined in algorithm 24.

Algorithm 24: search_alias_table(r)

```

1 Input: alias array  $A$  with size  $M$  storing reaction indices and cut-off array  $Q$  with size  $M$ 
   storing cut-off probabilities, and a random number  $r \sim norm(0, 1)$ 
2 Output: a candidate reaction  $R_\mu$  with probability  $\frac{\bar{a}_\mu}{\bar{a}_0}$ 
3  $\mu = [Mr]$ 
4  $r = Mr - \mu$ 
5 if  $r < Q_\mu$  then
6   return  $\mu$ 
7 else
8   return  $A_\mu$ 

```

3.5.9.3.3 Algorithm An implementation of RSSA with table-lookup search is outlined in algorithm 25.

3.5. REJECTION BASED STOCHASTIC SIMULATION ALGORITHM

Algorithm 25: Rejection-Based SSA (RSSA)()

```

1 Input: a biochemical reaction network of  $M$  reactions in which each reaction  $R_j$ ,  

    $j = 1, \dots, M$  is accompanied with the state change vector  $\vec{v}_j$  and the propensity  $a_j$ , the  

   initial state  $\vec{x}_0$  at time 0 and the simulation ending time  $T_{\max}$ 
2 Output: a trajectory of the biochemical reaction network, which is a collection of states  

    $X(t)$  for time  $0 \leq t \leq T_{\max}$ 
3  $t = 0$ 
4  $\vec{X} = \vec{x}_0$ 
5 build the species reaction SR dependency graph  $\mathcal{G}$ 
6 foreach  $S_i \in Species$  do
7   define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
8  $\bar{a}_0 = 0$ 
9 foreach  $R_j \in Reactions$  do
10  compute  $\bar{a}_j$  and  $\underline{a}_j$ 
11   $\bar{a}_0 = \bar{a}_0 + \bar{a}_j$ 
12 build alias tables for  $M$  probabilities  $\frac{\bar{a}_j}{\bar{a}_0}$  by build_alias_table()
13 while  $t < T_{\max}$  do
14   repeat
15      $u = 1$ 
16     accepted = false
17     repeat
18       generate three random numbers  $r_1, r_2, r_3 \sim norm(0, 1)$ 
19       select  $R_\mu$  by build_alias_table( $r_1$ )
20       if  $r_2 \leq \frac{a_\mu}{\bar{a}_\mu}$  then
21         accepted = true
22       else
23         evaluate  $a_\mu$  with state  $X$ 
24         if  $r_2 \leq \frac{a_\mu}{\bar{a}_\mu}$  then
25           accepted = true
26        $u = u \cdot r_3$ 
27     until accepted
28      $\tau = \frac{1}{\bar{a}_0} \ln(u)$ 
29      $\vec{X} = \vec{X} + \vec{v}_\mu$ 
30      $t = t + \tau$ 
31   until  $\exists(X_i \notin [X_i, \bar{X}_i])$ 
32   foreach  $X \notin [X_i, \bar{X}_i]$  do
33     define a new  $[X_i, \bar{X}_i]$  around  $X_i$ 
34     foreach  $R_j \in ReactionsAffectedBy(S_i)$  do
35       compute new propensity bounds  $\bar{a}_j$  and  $\underline{a}_i$ 
36       update  $\bar{a}_0$ 
37   rebuild alias tables for  $M$  probabilities  $\frac{\bar{a}_j}{\bar{a}_0}$  by build_alias_table()

```

3.6. RSSA

3.5.9.3.4 Discussion The alias table lookup takes one comparison and at most two memory accesses, so $O(1)$. The constant time search is affected by a large computational cost for rebuilding the lookup tables, which is $O(M)$, but the average number of times the lookup tables rebuild is controllable through the fluctuation interval.

3.6 RSSA

The Rejection-based Simulation Algorithm seems to be an approximation, but everything is exact. It tries to reduce computation complexity, but instead of limiting the amount of random numbers, it focuses on another bottleneck: the computation of the reaction propensity.

The computational problem becomes more complex if we do not rely on mass action. The RSSA Algorithm therefore tries to reduce the number of times in which we compute the reaction propensity. We will need a placeholder and at the same time to keep the computation exact. Instead of using the state of the system, we use a *fluctuation interval*(a bound). From the state of the system X we generate a lower and upper bound; to do so, we just use a parameter providing a percentage, which is called δ ($0 < \delta < 1$). Therefore, the bounds will be computed as:

- lower $X = X - X \cdot \delta$
- upper $X = X + X \cdot \delta$

Given that the events of the reaction are modifying a few molecules per time, we can assume that for a certain amount of steps we will remain inside the same range of variability. We are trying to obtain a propensity computed over bounds; by doing so, we can apply the same computation for a higher number of steps, as we only need to recompute the propensity outside of the fluctuation interval. We can also compute the upper bound for the sum of the propensities \bar{a}_0 . a_1 will be in the middle, but we do not want to compute it. It seems like working with these bounds does not lead to an exact simulation: we need to avoid as much as possible the exact computation of the propensities.

Indeed, in the vast majority of cases we will have the possibility to choose the reaction without the real propensity. We will perform some computations and, given the presence of bounds, we will do some mistakes; the algorithm will evaluate the results and eventually reject them (rejection-based algorithm). For doing so, the algorithm generates the events with the upper bound of the propensity \bar{a}_0 . By using an upper bound τ will be lower, so we will generate more events with respect to the direct method. We apply a sort of Gillespie, we replace the standard propensity with the upper bound and choose the reaction as in the direct method. How can we understand whether an event is real or fake? In the case in which $\bar{a}_0 = a_0$ we are in the standard Gillespie. We should apply a similar reasoning as NRM for scaling for checking the validity of candidate reactions.

Let's imagine that we are selecting R_2 : we should generate another random number, scale it over the bound and understand if we are in the exceeding (fake) or inside (real) area.

- If the random number is lower than the lower bound, we can accept it without computing the real propensity.
- If the random number is between the bounds we require the exact propensity for discriminating:
 - $a_2 < u < a_2$ accept

3.6. RSSA

- $a_2 < u < \bar{a}_2$ reject

The higher the fluctuation interval, the higher the uncertainty but lower the complexity → find the right compromise with some heuristics on δ value.

Chapter 4

Approximation algorithms

Can we assume that in any condition the stochastic simulation bottleneck is a problem? It depends. If we are in a condition in which all species are present in low number and it takes a lot to cure, the stochastic simulation is not really a bottleneck. We might have an issue if we wish to simulate for a long time, as we require multiplicative factors. At the moment, it is not feasible to compute an exact stochastic simulations for all the models that we need to observe, in particular for a huge number of species and reactions. Therefore, there is a huge research in developing alternative strategies that allow to compute the system in an *accurate* way (lose correctness) with lower computational cost and time. Why should we decide to use approximations in simulations?

1. it might be the only possible and feasible solution to solve a problem.
2. reality is affected by error, so even when we are using exact stochastic simulation algorithms we should consider a small degree of approximation. A certain deal of error could aid in retrieving a more realistic result.

In chapter 3 all the algorithms were belonging to exact stochastic simulation setting, so the result is the same. Instead in this case, each algorithm (Figure 4.1) approximates in a different way, we assume different approximations → not a consistent set. We should observe that of the three main computational strategies presented here, there is one which is much more popular with respect to the others. The τ leaping method is well known and has been further developed, so we will be focusing on it.

Before introducing the algorithm, let's try to think about the possible bottlenecks which could prevent us from having a fast algorithm. We could improve:

- work on the number of reaction events, group them in such a way to reduce the number of reactions in the system. The τ leaping methodology is working in this direction
- improve the computation of the propensity. For instance, the probability-weighted Monte Carlo is particularly promising in situations in which we have huge differences in propensities among reactions.

4.1 Probability-Weighted Dynamic Monte Carlo Method

The probability-weighted dynamic Monte Carlo method (PW-DMC) is an approximation approach for improving the computational efficiency of stochastic simulations of reaction networks where some

4.1. PROBABILITY-WEIGHTED DYNAMIC MONTE CARLO METHOD

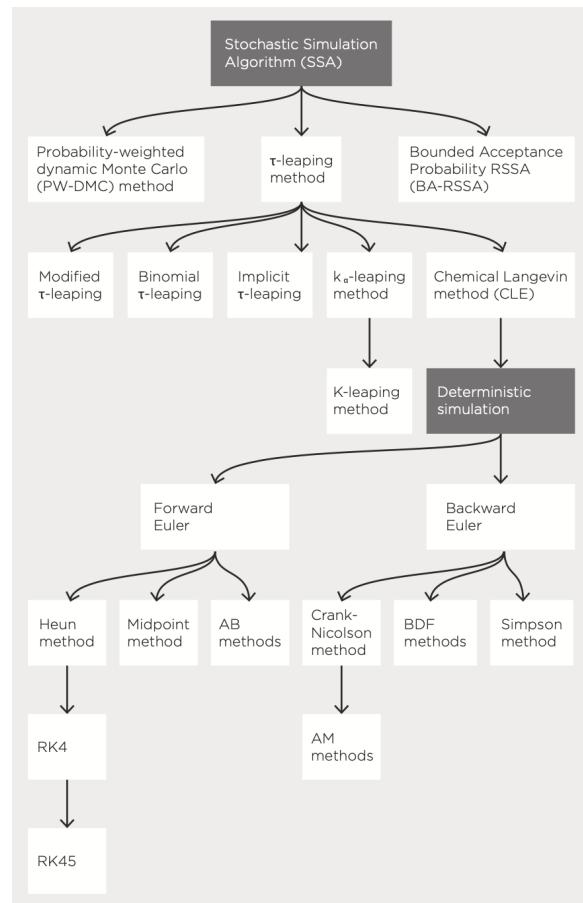


Figure 4.1

4.2. BOUNDED ACCEPTANCE PROBABILITY RSSA

reactions have propensities significantly larger than other reactions. The principle of this algorithm is a sort of modification of the probability distribution NRM through *weighted sampling*. The idea is to introduce a bias weight value on the propensity, in order to take into the account the number of times in which the reaction is executed.

We will have a lower amount of iterations at the price of applying reactions a different number of times according to the probability. The weight is a multiplicative factor of the stoichiometric coefficient. μ is the smallest reaction index μ such that:

$$\sum_{j=1}^{\mu} a_j^w \geq r_1 a_0^w$$

Second, PW-DMC has to correct the firing time τ of reaction R_μ because it is selected through the weighted sampling. The generation of τ is adapted from SSA in which it is generated from an exponential distribution with rate a_0^w . PW-DMC then updates the state at time $t + \tau$ by assuming that there are w_μ consecutive firings of R_μ in the time interval $[t, t + \tau]$. This methodology started to provide some hints for the approximation setting. In the complete algorithm we have the concept of effective propensity, allowing to reach the speed up.

4.2 Bounded Acceptance Probability RSSA

If we compare RSSA and DM algorithm, the main difference is that the RSSA algorithm is more complex than DM at each iteration. The bottleneck in RSSA is that we use the third random numbers for the rejection test, so this algorithm tries to speed up the process and reduce the complexity. If we decide to accept everything, we will end up with a strong bias. In order to avoid the high computational costs, we can only apply rejection to some cases → set up bounds, reaching bounded acceptance probability RSSA. If the probability of the candidate reaction is greater than certain amount, we accept it without the rejection test. Algorithm: we are still executing one reaction at a time. Comparing in terms of accuracy, the approximation of the previous method is not applied. Here we are not working with the real propensity. In this version we are totally avoiding the rejection-based part, the approximation in this case increases the error. It could be possible to apply a strategy in which we apply rejection based only in certain conditions (more complex). By looking at the literature, it is interesting to rank strategies in terms of accuracy and time.

4.3 τ -Leaping Method

The τ -leaping method is a stochastic approximate algorithm for improving performance of stochastic simulation. Its aim is to discretize the time axis into time intervals and to approximate the number of reactions firing in each time interval. The simulation then leaps from one time interval to the next interval with many reaction firings performed simultaneously. What is remarkable here, is that we are doing an approximation over the number of iterations which is much more relevant than previous approaches. We are grouping a mixture of events, which can be defined as a *macrostep*. If τ is big, the number of iterations will be low and the complexity will decrease. We should constraint the error in such a way that we are aware of its value as a constant. Which could be a high-level property of tau to apply macrostep without a crude error in the simulation? We should impose certain logics on τ .

4.4. CHEMICAL LANGEVIN METHOD

We want to limit the bias on the propensity. This translates in tau selection satisfying the so-called “**leap condition**”:

There exists a leap $\tau > 0$ such that the change in propensity a_j of each reaction R_j with $j = 1, \dots, M$ during the time interval $[t, t + \tau]$ is negligibly small. Negligibly small means lower than some threshold.

By applying a proper reasoning we reach the following formula, in which we derive the update of the state. Once we have selected τ , we will evolve the system by adding to the current state a certain amount of firing for each one of the reactions in the system [for each reaction j from 1 to m we apply a certain amount of time].

$$X(t + \tau) = \mathbf{x} + \sum_{j=1}^M k_j \mathbf{v}_j = \mathbf{x} + \sum_{j=1}^M Poi(a_j(x)\tau) \mathbf{v}_j$$

k_j will be generated through a Poisson distribution, which will depend over the specific propensity multiplied by the size of the step. The algorithm is applying any of the reactions per a specific amount of time.

- Pros: we are allowed to work with higher τ with respect to exact stochastic simulations.
- Cons: if we only have rare events, the algorithm will not be the best solution (as it will try to apply all reactions at all the times).

Given however that in any system there are at least some reactions with high propensity, at the very end we still gain a huge speed-up.

4.3.1 Choosing tau - Leap selection section

4.3.1.1 Postleap Selection

Choose a τ from a Poisson distribution and see if it is fine for the simulation. We start from a predefined arbitrary τ (small), then we have a trial procedure. The algorithm will compare the difference in the propensity before and after, to assess whether τ is of the right size. E.g. if the change in propensity is small, we can use a greater τ . The complexity of the τ -leaping is moved to a sub-problem, which is the choice of τ . We could also perform a preleap selection or choose other strategies. The Poisson distribution could provide more events than the ones that are possible in the system; in this case we end up with a negative population. While performing τ -leaping, we will need to make sure that a negative scenario is never reached through a test. The real amount of time executing k should be computed as the mean from k generated from Poisson distribution and the availability of the reactants [non chiaro]. We can bridge τ -leaping with exact stochastic simulation when we have only rare events.

4.4 Chemical Langevin Method

We can use the Normal distribution instead of Poisson, and scale it with mean and variance with another Normal formula based on a $(0,1)$ distribution, obtaining a simplified method. We will not have main events, but main *drivers* in the system. Stochasticity is strongly approximated, we are moving to an idea of average, real numbers. This will be the starting point for the deterministic

4.4. CHEMICAL LANGEVIN METHOD

simulation.

COPASI is a well-known simulator. It exploits Gillespie's algorithm and τ -leaping algorithm. In general, any simulator offers many algorithms, so we should be able to choose the best computational approach → calibrating the model. The stochastic rate provides us the speed, we require to derive it with some methods; all simulations algorithm compute deterministically or stochastically a speed for the reaction, computed over parameters of the model e.g. the rates. The rates, as the initial values, are not free-lunch, they can be derived through experiments. Often times, we work with models with not fully known parameters; in the second module we will explore solutions for *estimating the parameters* (reverse engineering approach).

Adaptive algorithms select a delta and change it adaptively during the simulation in order to reach the best results, for instance post leap τ selection. **Chemical Langevin Method** allows to modify the evolution of the system; the update formula depends on the propensity, but allows to distinguish a totally deterministic part from the stochastic one. This algorithm also has an important difference with previously seen strategies: we do not have integers, we will be provided with a real number adding some noise. This dynamics is over continuous numbers, tends to an average behaviour.

Chapter 5

Deterministic simulations

A *deterministic* way of calculating the dynamics of a system, when the last (noise) term of CLM equation becomes negligibly small compared with the second one, can be applied. This happens in the limiting case $a_j(\mathbf{x})\tau\beta\infty$, $j = 1, \dots, M$, and the deterministic simulation produces an average behaviour of the system that is very close to the one that results by averaging an infinite number of stochastic simulations of the system starting from the same initial state. If we work in terms of *moles*, we are moving Avogadro numbers; it is not so distant from the reaction size, the assumption is correct enough.

The deterministic simulations should give as an output the same result as an average stochastic simulation. ODEs can be safely used to simulate a biochemical system that satisfies the spatial homogeneity and continuum hypothesis.

5.0.1 Continuum hypothesis

“A biochemical system satisfies the continuum hypothesis if the number of molecules for each species is large enough to safely approximate molecular abundances by concentrations that vary continuously (as opposed to integer-valued molecule counts).” Sometimes, models simply use the ODE formalism, regardless of the hypothesis (since the ODE is the only computational framework allowing to reach the end of the simulation).

We are required to apply conversions and derive the ODE according to the following tables. In Figure 5.1 here we are not considering the combination of the reactants. c = stochastic rate, k = deterministic rate.

Reaction type	Reaction	Rate	ODEs
Zero-order reaction	$\emptyset \xrightarrow{k} A$	k	$\frac{d[A]}{dt} = k$
First-order reaction	$A \xrightarrow{k} B$	$k[A]$	$\frac{d[A]}{dt} = -k[A]; \frac{d[B]}{dt} = k[A]$
Second-order reaction	$A + B \xrightarrow{k} C$	$k[A][B]$	$\frac{d[A]}{dt} = \frac{d[B]}{dt} = -k[A][B]; \frac{d[C]}{dt} = k[A][B]$
Second-order reaction (same reactant)	$A + A \xrightarrow{k} B$	$k[A]^2$	$\frac{d[A]}{dt} = -2k[A]^2; \frac{d[B]}{dt} = k[A]^2$
Third-order reaction	$A + B + C \xrightarrow{k} D$	$k[A][B][C]$	$\frac{d[A]}{dt} = \frac{d[B]}{dt} = \frac{d[C]}{dt} = -k[A][B][C]; \frac{d[D]}{dt} = k[A][B][C]$

Figure 5.1: Table 4.4 Marchetti’s book

5.1. DETERMINISTIC APPROXIMATION

Reaction order	Reaction	Deterministic rate constant	Unit
Zero-order reaction	$\emptyset \xrightarrow{c} A$	$k = c/(N_A V)$	$\text{concentration} \cdot \text{time}^{-1}$
First-order reaction	$A \xrightarrow{c} B$	$k = c$	time^{-1}
Second-order reaction	$A + B \xrightarrow{c} C$	$k = c N_A V$	$\text{concentration}^{-1} \cdot \text{time}^{-1}$
Second-order reaction (same reactant)	$A + A \xrightarrow{c} B$	$k = c N_A V / 2$	$\text{concentration}^{-1} \cdot \text{time}^{-1}$
Third-order reaction	$A + B + C \xrightarrow{c} D$	$k = c (N_A V)^2$	$\text{concentration}^{-2} \cdot \text{time}^{-1}$

Figure 5.2: Table 4.5 Marchetti's book

As shown in Figure 5.2 it is possible to go back to the stochastic setting from the deterministic one. CLM equation: if we assume that the product is crazily high i.e. close to infinite, we can assume that the two parts of the equations have different orders; in this specific condition, the noise part becomes negligible.

5.1 Deterministic approximation

If the propensity is approaching infinite, we can assume that the deterministic setting is motivated. We are required to introduce the law of mass action and employ tables [last lecture] to derive a set of ODEs. In this context, the law of mass action is a bit different from what we have observed at the beginning of the course. We need to remember that the constant of proportionality, i.e. rate, is not the same as the stochastic setting.

$$\frac{d[S_i]}{dt} = \sum_{j=1}^M (k_j \mathbf{v}_{ji} \prod_{l=1}^N [S_l^{\mathbf{v}_{jl}}]), i = 1, \dots, N.$$

The equation $\frac{d[S_i]}{dt}$ should represent a molar concentration over time. We have an equation for each of the species $i = 1, \dots, N$. It should take into consideration the effect of all substances in the system \rightarrow sum over M , considering all reactions, which will be multiplied by the stoichiometric index. The system is computed as k (constant of proportionality), stoichiometric index and the product of all the reactants. If a species is not a reactant, $S_i = 0$, we end up with 1, only product of the reactants.

$$\frac{d[A]}{dt} = -\frac{d[B]}{dt} = -V_{MAX} \cdot \frac{[A]}{K_M + [A]}$$

We can just rely on a simplified set of equations to avoid mass action correspondence. V_{MAX} = maximum velocity of the enzymatic reactions, K_m , called *Michaelis constant*, indicates the concentration of the substrate at which the reaction rate is half of its maximum value.

5.2 Numerical solution of ODEs

Often times in computational biology it is unlikely to have enough power for deriving an analytical solution of the system, reality is different and the complexity prevents this kind of approach. Therefore we rely on numerical methods to compute the simulation, adding an additional layer of approximation. The algorithm uses the idea of derivative to understand the next value. For a value of $t > 0$, the level of approximation could be remarkable and depends on the dynamics of the system. Remember that when we simulate in time we have the issue that the computation of the next state

5.2. NUMERICAL SOLUTION OF ODES

depends on the previous state: we are dealing with an iterative formula, so potentially we can have a huge error explosion. At the basis of such method is the concept of derivative and geometrical rule to identify next step; Euler's method is the simplest one.

5.2.1 Euler's method

The first examples of explicit/implicit numerical methods are the *forward Euler method/backward Euler method* for updating the system state:

- Forward Euler: $[X_{n+1}] = [X_n] + hF(t_n, [X_n])$
- Backward Euler: $[X_{n+1}] = [X_n] + hF(t_{n+1}, [X_{n+1}])$

Not surprisingly, for increasing the order of the algorithm we will require a more accurate approx of the derivative, translating in additional evaluation of the ODE.

5.2.2 RUNGE-KUTTA Method

RK4 is a 4th order method, good compromise in accuracy and computational requirements. This algorithm uses a sort of average over Ks, which are computed by solving the set of ODEs as following:

$$K1 = F(t_n, [X_n]) \quad K2 = F(t_n + 2h, [X_n] + h2K_1) \quad K3 = F(t_n + h2, [X_n] + h2K_2) \quad K4 = F(t_n + h, [X_n] + hK_3)$$

- . Is it possible to increase accuracy without increasing complexity?

5.2.3 Midpoint method

2nd order method, we compute the new state at line 5 by two elements: x the current state and x old (the previous one). In this case, the multi-step method links the increased order to the number of step previously considered to compute the slope.

Drawback: what happens in the first step? We require an initial state and and additional time series! Limitation of multi-step algorithms: they all require a discretization step, it rules the movement. The time should not be computed during the iteration, chosen from the beginning; if we think about this, it can be a limitation of the application of the methodologies, which ask the user an information which might be unknown.

Which is the right time for simulating? Of course we can try to keep the discretization step as small as possible, but the right question that should be asked is: which is the error value? Keeping the error below a certain threshold is not easy, since the dynamics evolve with the system. In order to achieve error control, we should apply more requirements to discretization, leading us to seek an *adaptive solution*. In order to derive a rough estimate of the error we should compare the state computed by two algorithms of different order: one should be more accurate than the other, to have an idea of the degree of approximation.

5.2.4 Adaptive methods - Runge-Kutta-Fehlberg

"Strapopular algorithm: Runge-Kutta-Fehlberg, RK45 for friends". RK45 is composed of two methods, 4th and 5th order to apply error evaluation [4th for dynamics, 5th for estimating the error]. The algorithm will scale the step (h), in such a way that we keep the deviation below an error threshold.

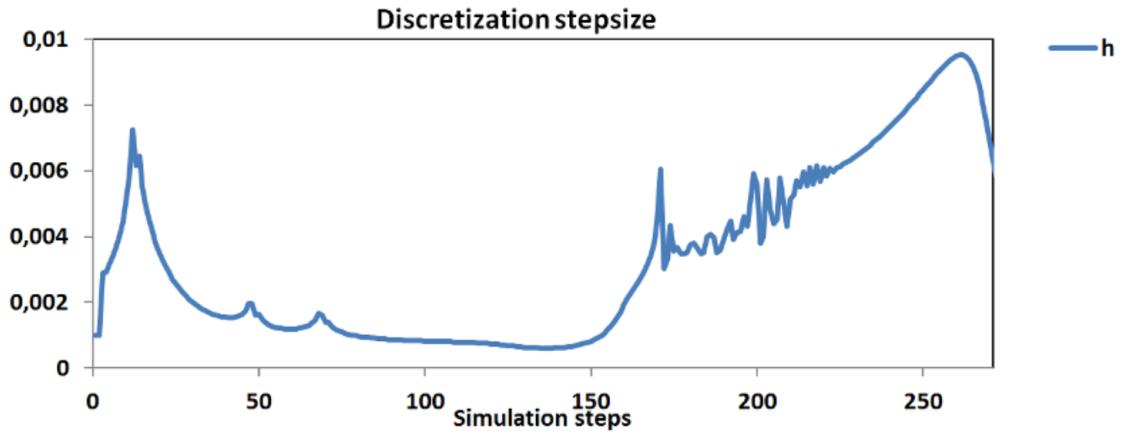


Figure 5.3: Figure 4.9 Marchetti's book

A formula will allow to play with h according to the deviation (increase if deviation is little). Recall that for the 5th order we require 6 derivations.

The two methods are similar, they share the same K_s , therefore at the price of computing a fifth order method we will have the possibility to obtain two evaluations \rightarrow quite efficient method. ODE45 is this algorithm! Error computation: $\Delta_{n+1} = \frac{\|[\tilde{X}_{*n+1}] - [X_{*n+1}]\|}{h}$. The error estimate is then compared to the error threshold ϵ_t provided by the user. If $\Delta_{n+1} \leq \epsilon_t$, the local truncation error is assumed to be smaller than the threshold, the state $[X_{n+1}]$ is accepted and the algorithm moves one step forward. In the other case, the new state is not accepted and the next state is evaluated again using a different (smaller) value of h . In both cases, the value of h is updated as:

$$h_{n+1} = h_n \sigma \sigma = \left(\frac{\epsilon_t}{2\Delta_{n+1}} \right)^{1/4}$$

Issue: it's possible that for specific dynamics we will need an infinitesimal h to satisfy the error threshold. We can avoid this by updating the strategy, for instance impose an additional threshold to h or insert an heuristic.

The value of h used at each step is plotted in Figure 5.3. We can end up in situations in which the system changes a lot \rightarrow *stiffness condition*, if we work with an adaptive method the property of the dynamics leads to instability in deriving the discretization step. Stiffness is a couple property of ODEs and the numerical scheme used to solve the system. This means that the same system of ODEs may exhibit stiffness only when it is simulated with some of the numerical schemes introduced in this chapter. In MATLAB we can use ODE15S in case of stiffness (happens quite often in biology simulations).

Chapter 6

Hybrid simulation approaches

Hybrid simulation combines the advantages of complementary simulation approaches: a system is partitioned into subsystems that are simulated with different methods. Sometimes we need to make a consistent choice for the complete model, but often (especially in biology) the model can incorporate many different situations. For instance, not all species will be present in low or high amounts. We cannot simulate with exact simulation strategies due to complexity, but at the same time for some parts of the network relying on approximation is too much and we risk losing some important details. We need to identify the qualities of the system that should be linked to a specific degree of approximation. When is it particularly dangerous to simulate deterministically? For instance, when rare events can occur: the stochastic nature of reaction firing cannot be fully modelled by deterministic setting. If the firing probability is lower than a threshold, we can assume that it is rare → intrinsically stochastic. We can divide reactions according to their firing probability, apply a rule over the propensity. If instead we focus on variables, we can select abundance levels: in case of low abundance, the stochasticity over the average is providing an important part of the behaviour. Usually, reactions with low propensity are also the ones modifying low abundance species. In highly abundant species, the contribution of noise is reduced.

- low number species and slow reactions → exact stochastic simulation
- high numbered species and fast reactions → approximation

In the scheme in Figure 6.1 we are trying to map the algorithms that we have already seen together, we are still not creating an hybrid method. Keep in mind that the availability of species can change along the trajectory. It is particularly difficult to make a consistent choice, therefore the hybrid setting is generally preferable in this case.

We need to partition the set of chemical reactions in subgroups in which we find consistent properties (Figure 6.2). Once the groups are established, we should be able to simulate the system in different settings. The main assumption in the tau leaping method is that the propensity of the reaction will not change dramatically during the macrostep; if we apply this concept to the hybrid setting we will see that this is an issue, as groups are not disjoined.

6.1 Reaction-Based System Partitioning

In order to divide reactions into group we can set up a threshold, which could be computed over the product of the propensity of the state and the simulation step. If the product is higher or lower than

6.1. REACTION-BASED SYSTEM PARTITIONING

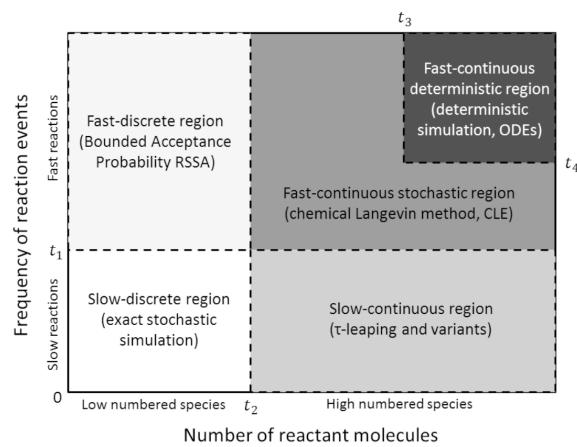


Figure 6.1

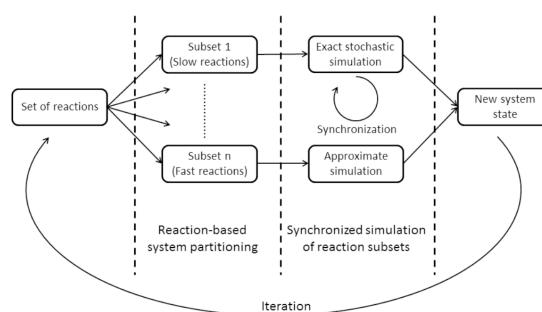


Figure 6.2

6.2. HRSSA

the threshold, we can identify the reaction as rare or probable. Example of partitioning algorithm: *two class reaction-based partitioning*. Divide reactions in slow and fast through an iterative loop. In general, we can increase the complexity of such approach as much as we want. Example: *four class reaction based partitioning*, we can bridge more simulation strategies. In Algorithm 45 the four class partitioning is applied; at the very beginning we impose a time step e.g. with tau leaping, compute the partitioning ending up with 4 sets (very slow, slow, medium and fast). For any of the reactions we will apply different strategies, for instance in the case of the very slow we require exact stochastic simulation. For sure the simulation will be more accurate, but we cannot claim that the simulation is exact, since we are only working on a set of reactions, not on the full system. If we wish to have an exact algorithm, we should consider the problem of **time varying reaction propensity**. If we want to be able to appropriately generate time, we should move considering the integral of the propensity over the time and the random number. We can consider the zero crossing of an equation as following (the log of the random number is a negative quantity):

$$\int_t^{t+\tau} a_0^s(X(t')) dt' = -\ln(r)$$

Instead of deciding τ at the beginning, the time will be computed along the approximation; when the quantity will be equal to zero, the approximation will stop and restart. We can consider this as a sort of traffic light: an event is generated, green light, we can move one. The real issue is that even if we have an equation to find the right time, being able to compute this requirement exactly with a computational strategy is a problem. The approach to zero will be affected by a variety of steps, e.g. the computer has a certain threshold for the zero. In addition computing the integral is computationally challenging.

1. non trivial complexity, integrals tend to be approximated by computers
2. the zero crossing is affected by approximation error

If we use deterministic simulation for simulating fast reactions, we can add another equation to understand when it is the time to stop during the simulation. We start from the logarithm of the random number and proceed with numerical integration.

$$\frac{dRES}{t} = a_0^x, RES(0) = \ln(r)$$

Synchronization has a price: the more complex, the higher impact we will have on the right time. Can we do something better? We can apply an extension of RSSA to obtain better results.

6.2 HRSSA

This algorithm claims to be exact and was developed by Marchetti. In RSSA we have a side effect: τ is computed over an *upper bound*, therefore we no longer need to reason in terms of propensity varying in time. By taking this perspective, we totally avoid slow events, just focus on upper bound. We have two main issues in this strategy:

1. by considering an upper bound we will generate more events
2. the bounds should be satisfied, therefore along the simulations we will need to check the consistency over the fluctuation interval of the state

6.2. HRSSA

Algorithm 47 Hybrid Rejection-based SSA (HRSSA)

Input: a biochemical reaction system with initial state X_0 , the parameter δ for calculating the fluctuation interval of the system state, the parameters τ^f , θ and γ for running Algorithm 42 and the simulation ending time T_{max}

Output: a trajectory of the biochemical system.

```

1: initialize time  $t = 0$  and state  $X = X_0$ 
2: while ( $t < T_{max}$ ) do
3:   compute the fluctuation interval  $[X, \bar{X}] = [(1 - \delta)X, (1 + \delta)X]$ 
4:   for all reactions  $R_j \in \mathcal{R}$  do
5:     compute reaction propensity bounds  $a_j$  and  $\bar{a}_j$ 
6:     update reaction partitioning (sets  $\mathcal{B}^s$  and  $\mathcal{R}^f$ ) by applying Algorithm 42 on the lower bound of the system state  $X$  according to input parameters  $\gamma$ ,  $\theta$  and  $\tau^f$ 
7:   end for
8:   compute  $\bar{a}_0^s = \sum_{R_j \in \mathcal{B}^s} \bar{a}_j$ 
9:   set  $updateNeeded = false$ 
10:  while ( $t < T_{max} \wedge \neg updateNeeded$ ) do
11:    set  $\tau = -\ln(r)/\bar{a}_0^s$ , where  $r$  is a random number in  $U(0, 1)$  (see Appendix B.1)
12:    compute  $X(t + \tau')$  by simulating fast reactions ( $\mathcal{R}^f$ ), at time steps of maximum length  $\tau'$ , according to an approximate algorithm (either stochastic or deterministic), where  $t + \tau'$  is the last computed time step such that  $\tau' \leq \tau$  and  $X(t + \tau') \in [X, \bar{X}]$ 
13:    if ( $\tau = \tau'$ ) then
14:      generate two uniform random numbers  $r_1, r_2 \sim U(0, 1)$ 
15:      set  $accepted = false$ 
16:      select the slow reaction  $R_\mu$  in  $\mathcal{B}^s$  with the smallest index  $\mu$  such that  $\sum_{j=1}^\mu \bar{a}_j > r_1 \bar{a}_0^s$ 
17:      if ( $r_2 \leq a_\mu / \bar{a}_\mu$ ) then
18:        update  $accepted = true$ 
19:      else
20:        compute  $a_\mu(X(t + \tau'))$ 
21:        if ( $r_2 \leq a_\mu(X(t + \tau')) / \bar{a}_\mu$ ) then
22:          update  $accepted = true$ 
23:        end if
24:      end if
25:      if ( $accepted = true$ ) then
26:        update  $X(t + \tau')$  by applying  $R_\mu$ 
27:      end if
28:      if ( $(X(t + \tau') \notin [X, \bar{X}])$ ) then
29:        update  $updateNeeded = true$ 
30:      end if
31:    else
32:      update  $updateNeeded = true$ 
33:    end if
34:    update  $X = X(t + \tau')$ 
35:    update  $t = t + \tau'$ 
36:  end while
37: end while

```

Figure 6.3: HRSSA algorithm

We have no need of computing the integral, we work with fluctuation intervals and link the generation of τ over this quantity, with the only difference that we only consider the upper bound and not the current value.

Pseudocode (Figure 6.3): we start from a while loop, we compute the fluctuation interval, the bounds of the propensity (same as RSSA) and move forward with τ computation. When we reach τ we decide to apply or not the reaction through random number generation. The main issue is how to compute the reaction partitioning, in this case the algorithm divide into slow and fast. Since we are working with bounds, we substitute the real propensity with the lower bound for performing the partitioning. Given that the partitioning is computed on the bound, it is just necessary to compute it again for each interval \rightarrow speed up. When the system is very complex, it is often not possible to apply this algorithm.

6.2.0.1 HSimulator

Simulator prototype (Java) developed by Marchetti to try HRSSA. We simply provide the set of reactions in arrow notation, same specification as MATLAB. The simulations provided are DM, RSSA, Euler, RK45 and HRSSA. We have the possibility to define simulation length and time sampling i.e. sampling over which the time series is stored.

Oregonator HRSSA: (Figure 6.4) the algorithm applies the stochastic approach by starting from the deterministic setting. In the advanced options we can insert additional specifications]. If we apply steady state conditions (simulation length = 5, time sampling = 0. 0001), we observe a

6.2. HRSSA

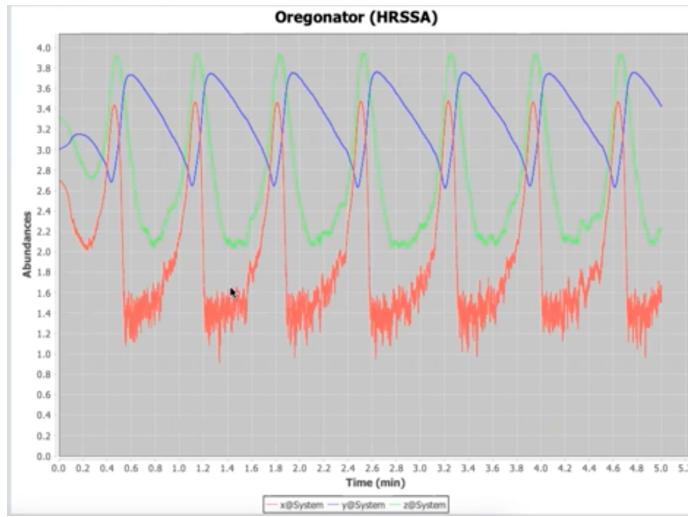


Figure 6.4: HSsimulator HRSSA Oregonator

flat signal; the issue is that the stochastic simulation is applied to the subset of slow reactions. If we change the parameters for deciding if something is fast or slow, we should see a change in the behaviour. By working with smaller variables, we see something remarkable: noise is heavily present.

Chapter 7

Reali

7.1 Introduction

The course follows the structure of the article *Optimization Algorithms for Computational Systems Biology*.

7.1.1 Definition of a system

A system is a set of integrated and interacting *components* or *entities* that form a whole with definite boundaries and surrounding environment. A system has a goal to achieve by performing one or more functions or tasks. Systems can be aggregated into a *hierarchy*. A system at a given level of detail can be a component at a higher level of detail.

- A *complex* (non-linear) *system* is a system that does not satisfy the principle of superposition, i.e., the behavior of the system cannot be inferred from the behavior of its components.
- A *dynamical system* is a system where fixed rules define the time dependencies of the system in a geometrical space. Dynamical systems have a space and time dimension because they change their characteristics over time. If we pick snapshots of the system at different time points, we observe different configurations of the system (data).

A *configuration* or state of the system refers to the current condition of the system and stores enough information to predict its next move. A state is characterized by the position of its components in a geometrical space and by the values of the attributes of its components (e.g., concentration or number of each elements involved). Systems change their state over time by changing the location of some of their components or changing the attributes of some of their components.

- *steady state*: some of the attributes of the system are no longer changing in the future.
- *transient state*: time needed to reach the steady state.

7.1.2 Determinism, nondeterminism, or stochasticity?

- *Deterministic systems* always react in the same way to the same set of stimuli. These systems are completely determined by the initial state and the input set. The essence of deterministic systems is that each event is causally related to previous events and choices are always resolved in the same way in the same context. When a system generates multiple

7.1. INTRODUCTION

outcomes from the same input in different observations, the system is **nondeterministic** (we cannot predict the output from the input).

- **Stochasticity** is the quality of lacking any predictable order or plan and stochastic systems possess some inherent randomness. It is possible to transform a nondeterministic system into a stochastic one by attaching probabilities to the selection points so that we turn nondeterministic choices into probabilistic choices.

7.1.3 Computational complexity

Complexity arises when interacting components self-organize to form evolving structures that exhibit a hierarchy of emergent system properties. An **emergent behavior** can be originated by a collection of components that interact in the absence of a centralized point of control to produce something that has not been designed or programmed in the system construction or evolution. Example: internet, ant colonies, consciousness.

Computational complexity is the amount of resources, measured as a function of the size of the input, needed to execute an algorithm.

- Computational space complexity: the amount of memory needed;
- Computational time complexity: the number of instructions to be executed.

7.1.4 Definition of a model

A *representation* is a set of symbols used to convey information and knowledge about a system. It is either physical as a cell or an ecosystem, or artificial as a computer network or an economic market. An abstraction is a representation that ignores some aspects of a system which are not of interest for the current investigation.

A *model* is an abstraction of a system. A model has its own interacting components that are characterized by the attributes that we want to observe. The set of all the attributes in a model is the *experimental frame*.

- A *dynamic model* aims at predicting the behavior of the system in time/space through what if analysis. **What if analysis** investigates how a change in some attributes affects the behavior of the modeled system.
- A *computational model* is a model that can be manipulated by a computer to observe properties of the corresponding system.

7.1.5 Checking the validity of a model

Validity is a fundamental property of models and witnesses the capacity of a model of making good predictions. We need to assess the validity of a model before using it to predict the behavior of a system.

Assume that M is a model for the system S and \underline{M} is the modeling process. Let $s(t)$ and $m(t)$ be the state of the system and of the model at time t , and f_s and f_m the state transition functions of the system and of the model, respectively. Finally, let $I_s(t)$ and $O_s(t)$ be the input and output of the system at time t . Similarly, we write $I_m(t)$ and $O_m(t)$ for the model.

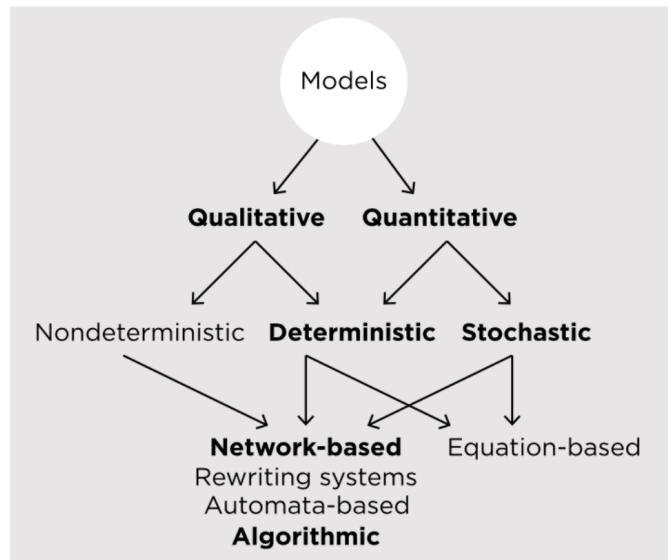


Figure 7.1: From a model to methods

What we expect is that going from one state to the other we have a function (one for the system and one for the model); in a mathematical model we integrate the f_m function to known what happens in the transition of the model, but we cannot do that in the real setting (the transition function f_s is not known) → when dealing with nature, we cannot validate models according to the previous definition, so we use I/O validity, based on known input and outputs of the system.

The input and output are here generalized concepts: input can be any perturbation of the system or of the model, and output can be any observable property causally related to the input.

A model M is valid for a system S if: $f_m(M(s(t_0))) = M(f_s(s(t_0))) = m(t_1)$
 I/O validity can be checked by using data sets produced by the model and observed and measured on the system. An issue in this comparison process is *overfitting*:

- a model is well tuned to a specific dataset used to build the model
- it performs poorly on other datasets

Cross-validation: check overfitting by testing the model on data sets different from the ones used to build and calibrate/train the model.

These concepts, even if usually referred to computational models, may apply to general models or representations of a system.

7.1.6 How to build a model

We need to define objectives:

- what do you want to model?

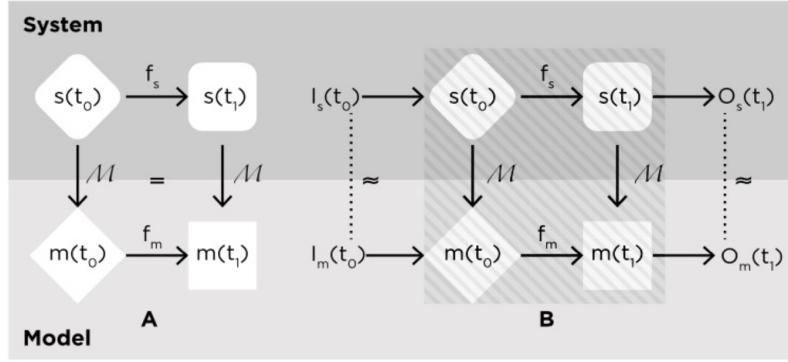


Figure 7.2: validation

- what do you want to investigate with the model?
- what do you expect from the model?
- why do you need a model?

After defining the question and gathering data, we need to build the model and calibrate it, in order to check if it can recapitulate data. If it does not, either we are missing something or we must tune some parameters. Different parameters can lead to dramatic changes in dynamics. Example: Lotka-Volterra model with different parameter conditions (Figure 7.4).

- A) shows periodic oscillations, same amount of preys and predators
 B) wider peaks and lower predator presence

7.2 Optimization problem

In general, it is a problem in which we try to *maximize* or *minimize* something. What we want to optimize is a function usually called *objective function* (or cost function). The function depends on a variable or a vector of variables, called unknowns or parameters or parameter estimates. They may be subject to certain constraints($<$, $>$, $=$).

7.2.1 General definition of an optimization problem

$$\left\{ \begin{array}{ll} \max_{x \in \mathbb{R}^n} f(x) & \\ c_i(x) = 0 & i = \mathcal{E} \\ f_j(x) \geq 0 & j = I \end{array} \right\} \text{ set of indexes } \quad \left[\begin{array}{l} \text{Constraints (equality and inequality)} \end{array} \right]$$

The model (for us) is a function that gives a certain interval/time, initial conditions and parameters, returns the variables at that time. (Assume deterministic description)

$$m : \mathbb{R} \times \mathbb{R}^{(n+1)} \times \mathbb{R}^m \rightarrow \mathbb{R}^N$$

where $n+1$ accounts for the dimension of variables and time.

$$(t_1, (\vec{x}_0, t_0), \theta) \mapsto \vec{x}_1$$

7.2. OPTIMIZATION PROBLEM

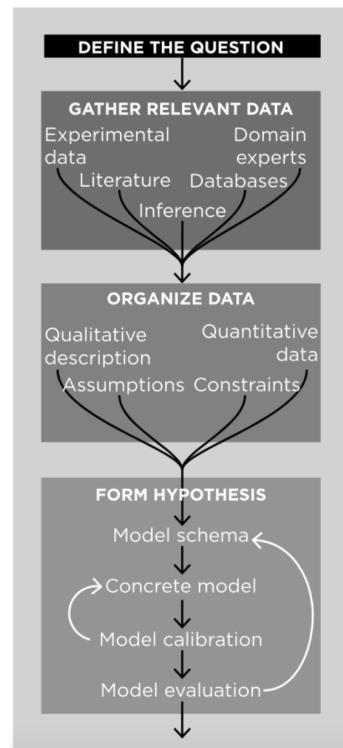


Figure 7.3: Workflow

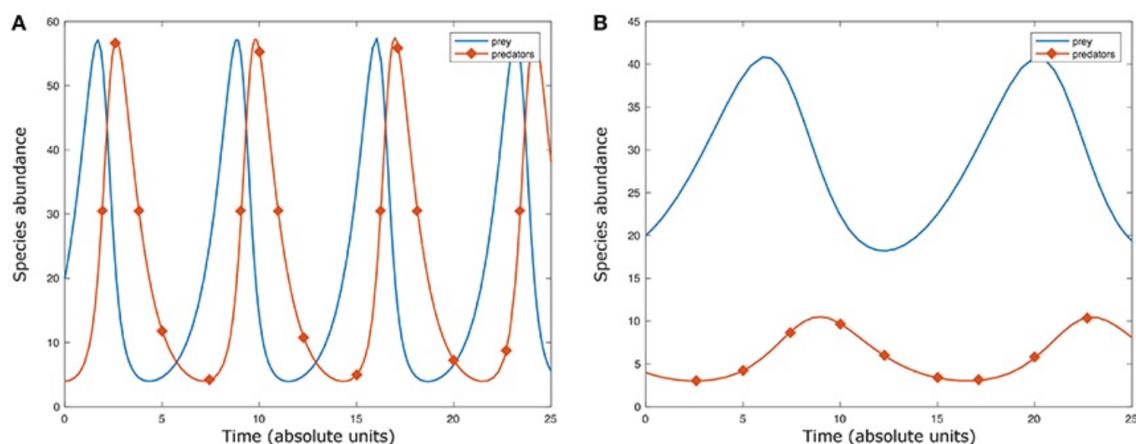


Figure 7.4: Volterra

7.2. OPTIMIZATION PROBLEM

Initial conditions in Lotka-Volterra: $((20, 5), 0)$.

θ represents parameters e.g. in Lotka-Volterra, a, b, β, α . Now, assume that we have k observations: $(t_i, \vec{y}_i), i = 1, \dots, k$, where $t_i \in \mathbb{R}^+$, $\vec{y}_i \in \mathbb{R}^\ell$ y in theory can be a subset, $\ell < N$: this happens a lot in complex systems, we may not observe all variables! For simplicity, we can assume $\ell = N$. Assuming that we can compute the following:

$$m(t_1, (\vec{x}_0, t_0), \theta) \in \mathbb{R}^N =_{\text{drop initial point notation}} m(t_i, \theta)$$

We can compute distance: $d_i = \vec{y}_i - m(t_i, \theta)$. We can choose any type of distance (Euclidean, max...). What we do is calculating point-wise the distance between the model and ‘true’ labels. It is quite common to use the **Euclidean distance**:

$$d\varepsilon = \sqrt{\sum_{i=1}^k (\vec{y}_i - m(t_i, \theta))^2} \rightarrow d\varepsilon = \sqrt{\sum_{i=1}^k \sum_{j=1}^N (y_{ij} - m_j(t_i, \theta))^2}$$

Sometimes we need to add weights, which multiply each component in the distances. We are putting together many outputs from the same model, so we might want to scale everything to make it more comparable. Furthermore, variables might be in different units of measurement, leading to biased results.

Observations:

- we do not want to reach “zero” when minimizing. Indeed, if the residual error = 0, we are 100% sure that we are overfitting the data.
- we need to really understand the data to construct the model
- we are manipulating θ in the space of the parameters, but we modify the output in the space of the observations: we are connecting abstract values to observations - like parameters for maximum likelihood.

Weights are multiplicative factors, sometimes we might wish to *transform* the distance.

Example: **Least squares algorithm**

$$d\varepsilon = \sqrt{\sum_{i=1}^k \sum_{j=1}^N W_{ij} (y_{ij} - m_j(t_i, \theta))^2}$$

Our problem is to minimize/maximize a function. Assume:

$$\min f(x), x \in \mathbb{R}^n$$

7.2.2 Definition of a minimum

A point x^* is called **minimum** if $\exists \varepsilon > 0 : \forall x : \|x - x^*\| < \varepsilon$

$$\Rightarrow f(x) \geq f(x^*)$$

[For the maximum $f(x) \leq f(x^*)$]

The minimum is **global** if $\forall x \in \mathbb{R}^n$ (or in our domain) $f(x) \geq f(x^*)$. In general it is not easy

7.3. GRADIENT METHODS

to determine global minimum/maximum, especially if we have a lot of dimensions. To find minima or maxima, we should impose $f'(x) = 0$.

We call a *stationary point*, a \bar{x} s.t. $f'(\bar{x}) = 0$.

7.3 Gradient methods

When we integrate to find ODE solutions, we do not obtain a function as a solution, just points. In our optimization problem we do not know f and f' (only sometimes we do), so we are required to use *numerical approximation*. The idea of looking at f' and set $f' = 0$ is still at the base of gradient methods.

If the problem contains constraints, how do we solve it? In this case the problem is:

$$\begin{cases} \max f(x) \\ g_i(x) = 0, \quad i \in \mathcal{I} \\ x \in \mathbb{R}^N \end{cases}$$

Let $\mathcal{I} = 1, \dots, m$. The traditional way to solve this problem is to translate this system to another function. The Lagrangian function is used to take into account the constraints.

7.3.0.1 Lagrangian function

We define the *Lagrangian function* as $L : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$ s.t.

$$L(x) = f(x) + \lambda g(x) = f(x) + \sum_{j=1}^m \lambda_j g_j(x)$$

7.3.1 Lagrangian Multipliers Theorem

If x^* is a stationary point for (Lagrangian function), then $\exists \lambda^*$ s.t. (x^*, λ^*) is a stationary point for L . It is a necessary condition (not sufficient, only one direction). This is a “bigger” problem, from $\mathbb{R}^N \rightarrow \mathbb{R}^N \times \mathbb{R}^m$. But still, I can search solutions using stationary points. We can generalize the idea to $g_i(x) \leq 0$, constraints

Remember that stationary points are not necessarily minima and maxima. We check whether a stationary point is a max/min through second derivations or evaluate the function in “other” points.

7.3.2 Definition of a gradient

Let $f : \mathbb{R}^N \rightarrow \mathbb{R}$ a differentiable function, we call gradient of f
 $\nabla f : \mathbb{R}^N \rightarrow \mathbb{R}^N$ sit. $\nabla f_i = \frac{\partial}{\partial x_i} f(x)_i$ and $\nabla f(x) = \begin{bmatrix} \frac{\partial}{\partial x_1} f(x) \\ \vdots \\ \frac{\partial}{\partial x_N} f(x) \end{bmatrix}$

We look for points for which the derivative vanishes $x^* : \nabla f(x^*) = 0$

TRY at home: $f(x, y) = (1 - x)^2 + 100(y - x^2)^2$

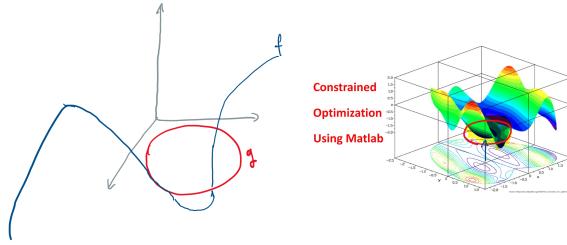


Figure 7.5: Blue = function, red = constraint

$$f(x, y) = -(y + 47) \sin \left(\sqrt{\left| \frac{x}{2} + (y + 47) \right|} - x \cdot \sin \left(\sqrt{\left| x - (y + 47) \right|} \right).$$

These two functions are used to test optimization algorithms. The first is **Rosenbrock's function**, the second the **Eggholder function**. Solving analytically these problems is hard. We cannot apply gradient methods for stochastic simulations, since the function is not continuous.

7.3.3 Limitations of gradient descent methods

One of the major limitations of these algorithms is that we are focusing on local minima, we never know if the distance is minimum. Furthermore, sometimes we want to optimize more variables and it might not be optimal to perfectly fit the solution to both of them → trade-off.

Figure 7.5: if we have an equality constraint we are only considering the points meeting the boundary (red). In an inequality constraint, we consider everything inside the red circle (yellow area). Generally, constraints reduce our search space; the Lagrangian tells us that the minimum point with some multipliers will give a solution of the Lagrangian, which is one function. If we find the solutions, we do not know if they are solutions of the original conditions, but they are ideal candidates that can then be checked.

For performing an evaluation of the distance we should integrate the model, which is computationally expensive. To do one integration we must perform a lot of computations. Our measure of computational cost is the number of times we have to simulate the model (per iteration).

In most cases, we do not know the gradient, therefore we should approximate it using the Taylor formula.

7.3.4 Gradient approximation with Taylor formula

$$(a, b) \in \mathbb{R}, x_0 \in (a, b)$$

Let $f_i(a, b) \rightarrow \mathbb{R}$ be differentiable $(n - 1)$ times in (a, b) and $f^{(n)}$ is continuous in x_0 . Then let $x \in (a, b)$, we have:

$$f(x) = f(x_0) + f'(x_0)(x - x_0) + f''(x_0) \frac{(x - x_0)^2}{2!} + \dots + f^{(n)}(x_0) \frac{(x - x_0)^n}{n!} + R_n(x) \text{ s.t. } \lim_{x \rightarrow x_0} \frac{R_n(x)}{(x - x_0)^n} = 0$$

We focus on the first terms $f(x) = f(x_0) + f'(x_0)(x - x_0) + R_2(x) = 0$
 $f'(x_0) = \frac{f(x) - f(x_0)}{x - x_0} + \left(\frac{R_2(x)}{(x - x_0)} \right) = \frac{f(x) - f(x_0)}{x - x_0} + R_1(x)$.

7.3. GRADIENT METHODS

We can also use this trick for $N > 1$

Let $f : \mathbb{R}^N \rightarrow \mathbb{R}$ and $e_i = (0, \dots, 0, 1, 0, \dots, 0)$. Let's consider $x_1x + \varepsilon e_i, x - \varepsilon e_i$; we are only moving along one direction. In this case:

$$f(x + \varepsilon e_i) = f(x) + \varepsilon \frac{\partial f}{\partial x_i}(x) + \frac{1}{2}\varepsilon^2 \frac{\partial^2 f}{\partial x_i^2}(x) + R_3(x) \\ f(x - \varepsilon e_i) = f(x) - \varepsilon \frac{\partial f}{\partial x_i}(x) + \frac{1}{2}\varepsilon^2 \frac{\partial^2 f}{\partial x_i^2}(x) + R_3(x) \Rightarrow f(x + \varepsilon e_i) - f(x - \varepsilon e_i) = 2\varepsilon \frac{\partial f}{\partial x_i}(x) + \varepsilon^2 \frac{\partial^2 f}{\partial x_i^2}(x)$$

We have computed an approximation of the first derivative with improved accuracy.

Consider that this only applies to one derivative, we have to perform this at least twice $\rightarrow 2W$. In order to obtain a decent gradient, we require a lot of computations, but they are fast (quite low number of iterations). We will see other methods, which are somehow more precise, but also heavier.

We can always check $\Delta f = 0$ or not to understand if we are done!

As we already saw, there might be points where the gradient vanishes which are not the final destination. Gradient methods may tend to overfitting, but they are effective. The main issue is that since we approximate the gradient, we do not trust it everywhere.

Gradient methods can be applied to two different categories of problems:

- constrained
- unconstrained
 - **line search algorithm:** follow a direction
 - **trust region:** create an approximation of the problem and solve it in a small trustable region

7.3.5 Line search

7.3.5.1 Newton's direction

If we consider Taylor's formula and let x_k be our starting point, let $\alpha \in \mathbb{R}^+$ step length and p our direction ($x_k, p \in \mathbb{R}^n$). For $n = 1$, we have:

$$f(x_k + \alpha p) = f(x_k) + \alpha p f'(x_k) + \frac{\alpha^2 p^2}{2} f''(x_k) + r(p^3)$$

For simplicity set $\alpha = 1$ and truncate the formula:

$$f(x_n + p) = f(x_n) + p f'(x_n) + \frac{p^2}{2} f''(x_n) = m_k(p)$$

\rightarrow instead of minimizing the initial f , we minimize the simple polynomial $m_k(p)$. From this equation we can get the direction $p = -\frac{f'(x_k)}{f''(x_k)}$, which is called *Newton direction* (best direction). When $n > 1$, $p = -(\nabla^2 f(x_k))^{-1} \nabla f(x_k)$. Finding the inverse of a matrix is “a pain”, not straightforward; this is why we will try to approximate this part.

7.3. GRADIENT METHODS

7.3.5.2 Line search algorithm for function minimization

Set $k = 0$ and guess an initial point x_0 WHILE $\|\nabla f(x_k)\| > 0$

1. compute $p_k = -(\nabla^2 f(x_k))^{-1} \nabla f(x_k)$
2. select α_k
3. update $x_{k+1} = x_k + \alpha_k p_k = x_k - \alpha_k (\nabla^2 f(x_k))^{-1} \nabla f(x_k)$
4. $k = k + 1$

We stop when the gradient is equal to zero, but we do not really have zeroes in our computers; therefore, we must apply a threshold ε .

At each iteration we have some issues:

- sometimes we require approximation to compute the inverse of a matrix
- it is computationally expensive to compute all these gradients

Nevertheless, going in this direction is smart. We can try to tackle the hardest part, i.e. p_k computation, by approximation.

7.3.5.3 Quasi Newton's direction

To avoid the computation of $\nabla^2 f$, we build iteratively a different matrix B_k , such that $B_{k+1} \cdot (x_{k+1} - x_k) = \nabla f(x_{k+1}) - \nabla f(x_k)$ [condition for the matrix]

We are approximating the second derivative as second of the gradient. Since we are already computing the gradient, we exploit it to prevent extra computations. The difference with respect to standard Newton direction is the Hessian, which is not computed here.

Quasi-Newton direction: $P_{k+1} = -\alpha B_{k+1}^{-1} \nabla f(x_{k+1})$

7.3.5.4 Steepest descent direction

We proceed in the direction that reduces the gradient the most:

$$p = -\alpha \frac{\nabla f}{\|\nabla f\|}$$

In this case we are completely ignoring the second derivative, we only focus on the gradient computation. This method converges slowly with respect to Newton and Quasi-Newton's direction.

7.3.5.5 Selecting α

Ideally, we want to define α s.t.

$$\bar{\alpha} = \arg \min_{\alpha > 0} f(x_k + \alpha p)$$

This is another optimization problem, ideal situation. To avoid solving the optimization, we usually consider α that satisfies :

$$f(x_k + \alpha p) \leq f(x_k) + c_1 \alpha \nabla f(x_k)^T p, c_1 \in (0, 1)$$

Armijo condition: the reduction should be proportional to α and $\nabla f(x_k)^T p$. Sometimes thing fails because of parameter choice: it is crucial to understand why functions fails and how parameters tuning can affect the most crucial steps in the algorithms.

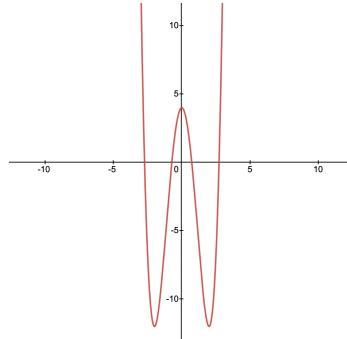


Figure 7.6: Desmos $f(x) = x^4 - 8x^2 + 4$

7.3.5.6 Convergence of a method

The order of convergence of a method (for us) is a constant ℓ , such that exists the limit:

$$\lim_{k \rightarrow \infty} \frac{\|f(x_{k+1}) - f(x^*)\|}{\|f(x_k) - f(x^*)\|^\ell} = L > 0$$

Where x^* is the solution and the method converges.

We compare the new iteration (numerator) to the old iteration (denominator); the limit should go to zero, the exponent is the speed - the higher the exponent ℓ , the faster will the upper term go to zero with respect to the bottom one i.e. faster convergence. The higher the exponent, the less iterations are required (in general). For the methods that we have previously seen:

- steepest descent: $\ell = 1$, linear convergence
- quasi-Newton: $\ell \in (1, 2)$, superlinear convergence
- Newton: $\ell = 2$, quadratic convergence

Example: $f(x) = x^4 - 8x^2 + 4$

$$x_0 = 3f'(x) = 4x^3 - 16x \Rightarrow f'(x) = 0 \Rightarrow x = 0, x = \pm 2, f''(x) = 12x^2 - 16$$

Algorithm: $f'(3) = 60, f''(3) = 92$,

Let $\alpha = 1$:

$$p_0 = -\frac{60}{92} = -0.65x_1 = 3 - 0.65 = 2.35, f'(2.35) = 14.31, f''(2.35) = 50.27, p_1 = -\frac{f'(x_1)}{f''(x_1)} = -0.28x_2 = x_1 + \alpha p_1 = 2.35 - 0.28 \cdot 2.35 = 1.35$$

Let's try the same by applying Steepest Descent method:

$$f'(3) = 60$$

$x_1 = x_0 \dots f'(3) = 60$ In this case the SDM is way faster, lucky shot. But what if we change the starting point? The direction will always be the same, i.e. $p_1 = -1$.

$$x_1 = 2.35 - 1 = 1.35, f'(x_1) = -11.75, x_2 = 1.35 + 1 = 2.35$$

We are doing ping-pong among two points!

7.3. GRADIENT METHODS

The fact that the second derivative progressively shrinks tells us that we need to reduce the step, but in this case we are not taking this into account. Of course we also have α , we should look at Armijo condition and change it. Take into account that each time that we are performing operation on a number we lose precision.

7.3.6 Trust region

[picture] Imagine that this is a cut function: our starting point x_k is in the middle. The main idea of the trust region is that we do not follow a direction: we approximate the function with a simpler function → Taylor approximation. According to how big and reliable the approximation is, we will choose a direction.

Last time we approximated the model as:

$$m(x_p + \alpha p) = f(x_k) + \alpha p^T \nabla f(x_k) + \frac{1}{2} \alpha^2 p^T B_k p$$

$$\alpha = 1, m_k(p) = f_k + p^T \nabla f_k + \frac{1}{2} p^T B_k p$$

7.3.6.1 Trust region steepest descent

Define a region such that $\|p\| < \delta_k, \delta_k > 0$ in which we solve the optimization problem (1) instead of the original. Remember that B_k can be the Hessian or an approximation; on the other hand, we have said that we can also ignore it.

Finding a minimum for $m_k(p) = f_k + p^T \nabla f_k$ means that we are looking for:

$$\min_p m_k(p) = \min_p (f_k + p^T \nabla f_k)$$

Remember that f_k is a constant, so we want to find a direction for which $\min_p p^T \nabla f_k$ is minimum. We can rewrite this as:

$$p^T \nabla f_k = \|p\| \|\nabla f_k\| \cos \theta$$

We minimize for p such that $\cos \theta = -1$ and $\|p\| = \delta_k$, where p s.t. $\|p\| \leq \delta_k$ [radius of the trust region].

$$\min_p p^T \nabla f_k = -\delta_k \|\nabla f_k\|$$

$$p = -\delta_k \frac{\nabla f_k}{\|\nabla f_k\|}$$

This result is exactly the equation from steepest descent. We are applying a condition on the region with δ_k . This direction and the whole approach is called trust region steepest descent.

We could follow the same idea by applying Newton or Quasi-Newton.

To evaluate if we can really trust our region, we define the *actual reduction* as:

$$\rho_k = \frac{f(x_k) - f(x_k + p)}{m(x_k) - m(x_k + p)}$$

By construction $m(x_k + p) \leq m(x_k)$.

- If $\rho_k < 0 \rightarrow$ reject p , we are not improving the real problem. Usually take $\delta_k = \frac{1}{4}\delta_k$
- If $\rho_k \simeq 1 \rightarrow$ maybe longer step

δ value can be tuned according to the needs. The approach is similar to RK method seen with Marchetti. Of course we have a grey area between 0 and 1, so we define a threshold e.g. $\rho_k < \eta$ and $\rho_k > \eta$. By default, MATLAB uses a trust region algorithm. Having something certifying that we are doing good or bad is a great thing in approximation!

7.3.6.2 Trust region algorithm

Let $\hat{\delta} > 0, \delta_0 \in (0, \hat{\delta}), \eta \in (0, \frac{1}{4})$

$k = 0, \varepsilon < 0$

REPEAT

obtain p_k s.t. $p_k = \arg \min_p m(x_k + p)$

compute ρ_k

IF $\rho_k < \frac{1}{4}$

$\delta_{k+1} = \frac{1}{4}\delta_k$

ELSEIF ($\rho_k < \frac{3}{4}$) AND $\|p_k\| = \delta_k$

$\delta_{k+1} = \min(2\delta_k, \hat{\delta})$

ELSE

$\delta_{k+1} = \delta_k$

IF $\rho_k > \eta$

$x_{k+1} = x_k + p_k$

ELSE

$x_{k+1} = x_k$

IF $\|\nabla f(x_{k+1})\| < 0$

BREAK

We stop if the gradient is sufficiently small. Our focus is on computing p_k . We then evaluate ρ_k to adjust parameters (which is simpler from what we have previously seen).

If we apply this algorithm to the example of last lecture, it happens that with $x_0 = 235$ and steepest descent $\rho_0 = 0.17 < \frac{1}{4}$, which tells us to reduce δ . The only thing that changes is ρ changes.

PROBLEM:

$$g(x, y) = x^4 + y^4 + xy$$

<https://www.benfrederickson.com/numerical-optimization/> play with learning rate, explore the site.

7.4 Least squares problems

Recall that if m is the model, we quantified the distance between the model output and data as:

$$m_j(t_i, (x_0, t_0), \theta) = m_{ij}(\theta) - \hat{y}_{ij}, \text{ for } i, j \text{ as lesson 2}$$

$r_{ij}(\theta)$ is called RESIDUAL and we shape it as a vector.

$$J_k = J(\theta_k) \left[\frac{\partial r_I}{\partial \theta_i} \right], i = 1, \dots, n, I = 1, \dots, n$$

Since the time points are given by the data, everything only depends on the choice of parameter theta, which is a vector of parameters. We can derive the residual according to theta. Our function to minimize is $f(\theta) = \frac{1}{2} \sum_{j=1}^m r_j^2(\theta)$. It will hardly go to zero, as our observations are affected by noise: we just need to explain data, not noise. If we have the distance of the single point we can see the effect of each parameter by looking at the derivative. Here we have that the gradient (Jacobian) will be telling us the relationship among model parameters and data.

$$\nabla f(\theta) = \sum_{j=1}^m r_j(\theta) \nabla r_j(\theta) = J(\theta)^T r(\theta)$$

The matrix notation is a more convenient way to express this gradient. While solving least squares problems we always exploit Taylor approximation.

Hessian matrix:

$$\nabla^2 f(\theta) = J^T(\theta) J(\theta) + \sum_{j=1}^m r_j(\theta) \nabla^2 r_j(\theta)$$

What's *magical* of this is that we can use $J^T(\theta) J(\theta)$ as approximation for $B(\theta)$ of our gradient.

If the problem is linear, $r(\theta) = A(\theta) - y$. The objective function $f(\theta) = \frac{1}{2} \|A\theta - y\|^2$ and $\nabla f(\theta) = A^T(A\theta - y)$, $\nabla^2 f(\theta) = A^T A$.

If f is convex $\Rightarrow \exists \theta^* \text{ s.t. } \nabla f(\theta^*) = 0 - A^T A \theta^* = A^T y$

We reach a normal equation, linear system (we know how to solve this). With general functions, this is not so straightforward; what we will do is approximating the problem with a solvable linear problem.

When we try to quantify the distance between the model and our points we can formalize the problem as:

$$r_i = m_i(t, \theta) - y_0 f(\theta) = \frac{1}{2} \sum_{j=1}^m r_j^2(\theta) \nabla f(\theta) = J(\theta)^T r(\theta) \nabla f(\theta) = J(\theta)^T J(\theta) + \sum_{j=1}^m r_j \theta \nabla^2 r_j \theta$$

Last time we already said that we will ignore the sum, for two reasons:

1. it contains second order derivatives, painful to compute
2. the Newton direction is a quasi vector

7.4. LEAST SQUARES PROBLEMS

So at every iteration k we solve the approximated problem

$$J(\theta_k)^T J(\theta_k) p = -J(\theta_k) r(\theta_k) J_k^T J_k p = -J_k^T r_k$$

This is a linear system which we can solve. In this case, we are solving:

$$f(\theta_k + p) = \frac{1}{2} \|r(\theta_k + p)\|^2 \simeq \frac{1}{2} \|J_k p + r_k\|^2$$

This is what we called normal equation for a normal least squares problem. Under certain hypotheses the method converges quadratically!

We discussed last time that Newton is quadratic convergent. Of course the matrix should not be singular, we need to be able to solve the system. We start with a problem in a special form, sum of squares. Thanks to this, we can rewrite the problem in a simpler way and perform an approximation, leading to solving a linear system at each iteration. This approximation guides us rapidly to a solution. We are applying linear search, by defining a direction and solving a new problem at each iteration. The biggest issue could be the non invertible matrix, but we can do something to circumvent the issue.

7.4.1 The Levenberg-Marquardt method

At each iteration, we solve the problem:

$$\min_{\|p\| \leq \delta_k} \frac{1}{2} \|J_k p - r_k\|^2$$

We can have a solution inside the trust region δ_k or on the border i.e. not the minimum, but the smallest value we can reach.

- case 1: β is a solution and $\|p\| \leq \delta_k \rightarrow \text{DONE}$
- case 2: $\|p\| = \delta_k$, then \bar{p} is a solution if and only if $\exists \lambda > 0$:

$$(J^T J - \lambda I) = -J^T r + \lambda(\delta_k - \|p\|) = 0$$

If we can push it a bit further from zero and the problem is still solved, we can think of it as a solution. If we are hitting the boundary $\lambda(\delta_k - \|p\|) = 0$, we want to move the matrix a bit from singularity. We will not use it very much, but it is a well known algorithm. It is one of the default MATLAB solvers. The Levenberg-Marquardt converges quadratically when we are close to the solution, while if the residuals are big it does not perform well.

7.4.2 Solving a problem with bounds

We have seen together that we can exploit the Lagrangian for the equality constraint, but we can have other boundaries. There are other approaches which allow us not to lose our approximation advantage. We can simply do **variable transformation**: instead of changing the problem, we change the variables. Example: $x \rightarrow e^x$, $\mathbb{R} \rightarrow \mathbb{R}_0^+$ [other example missing, cannot understand from recording]

Another solution could be to include the bound in the **trust region**.

[drawing missing] *Evolutionary algorithms* follow the evolution of the solution: at the beginning look for solutions, then add a penalty for the boundaries.

7.4.3 Solving global minimum problem

How can we be sure that we are looking at a global minimum? We can start from another initial point and check whether the solution reaches the same minimum. From local to global → the *multi-start approach*, t is a shortcut, but the best way to work.

7.4.4 Gauss-Newton method

Let $N \in \mathbb{N}, \varepsilon > 0, J$ as defined before. We randomly select N vectors and use $\theta^1, \dots, \theta^n \in \mathbb{R}^n$

For each $i = 1, \dots, N$ DO

REPEAT

$\bar{J} = J(\theta^i)$

compute q s.t. $\bar{J}^i \bar{J} q = -\bar{J} r(\theta^i)$

compute $\vartheta = \theta^i + q$

compute $\varepsilon = \left\| \frac{\theta^i - \vartheta}{\theta} \right\|$, relative increase

update $\theta^i = \vartheta$

IF $\varepsilon < \bar{\varepsilon}$ then BREAK

SAVE θ^i

END

→ no global minimum guarantee!

There are other ways to detect if a minimum is global e.g. we try to divide the space in N different sectors and pick points for each one of them, *Latin hypercube* and *orthogonal sampling*. The more we do it, the more we acquire confidence, but we will never be sure. In addition, we always have to deal with noise, we do not know if the minimum is the best or we are overfitting.

Example on MATLAB: if we take only 10 random points we can have a biased result. By taking a bigger sample, we should somehow achieve a fuller result in the region. Still, we have some holes and repeated points. Are there smarter ways to take random points?

7.4.5 Latin hypercube sample

Get random numbers dividing the interval in m sectors. This is a 2x2 problem and we need to reason on some aspects: if we take the square $(0,1), (0,1)$ out of 100 points we will just have $3/4$ there → not exploring it very well. If parameters are between 0.1 to 1000 we need to better sample.

$n = 20$, the fewer points we get, the more we see the difference among the two methods.

$n = 200$, still we have missing parts.

$n = 2000$, thousands of iterations → if we zoom in there is still a lot of space

The takehome message is that it is almost impossible to cover all the space with points. Luckily these are starting points, if they are close to the solution we will have the good direction. Gradient methods are expensive, but they are smart.

7.4.6 MATLAB

When an optimizer stops, it gives as output the function converged to the solution or why it stopped. Termination criteria: gradient, incremental step e.g. is our step too small?, change in x was less of certain tolerance, the residual was less than specific tolerance, max number of iterations. These conditions are added in order to avoid infinite function evaluation.

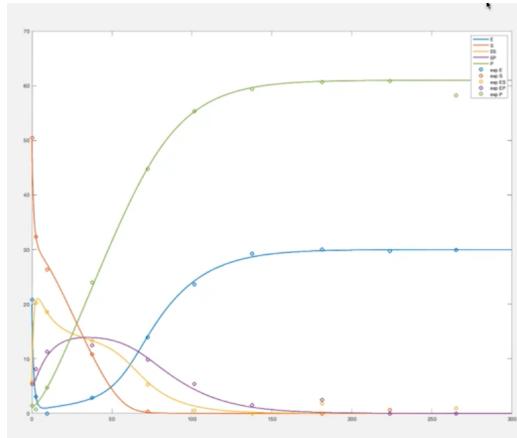


Figure 7.7: MATLAB multi-start lsqnonlin

We first need to define an enzymatic reaction as a set of ODEs. We then specify initial concentrations and a given set of rates. Integrate the model and plot the simulation results.

The dots are the experimental points, lines are the output of the simulation. According to different starting points, we will obtain different results; we need to quantify how much the model is distant from the real data. The output of the normal simulation is a set of points; we can do a linear interpolation for time and values, giving how much is each of the simulated variables at the requested time. Once we have the values at the right time, we can compute the *residuals* through the sum of squares. In some cases we can also look at weighted residuals and normalize them; however, zeros are problematic → our experimental data goes to zero, we stick to normal SSE.

Our objective function takes the rate, experimental time and values, initial and final time. We call the solver (15s as the system is stiff, we require a more robust iteration) and get a vector of residuals and SSE.

If we compute the residual with s_1, s_2 and s_3 we can easily understand which is the better one (matches visual inspection of the plot).

We can then optimize and find the solution with `lsqnonlin` e.g. $SSE1 = 33.6653$, $resNorm = 38$, worse, we should improve initial conditions.

[Recap from last time]

MATLAB multi-start is a wrapper working with different algorithms. It will automatically parallelize the problem. It requires to insert starting points and tolerance. We therefore define bound, create problem and give initial points e.g. `lsqnonlin + objective function`. The output contains the result of parallel `lsqnonlin` and parameters, somehow similar to what we saw before. We can reduce the bounds, but solution 1 is still the best. Main limitation: heavily depends on the number of initial points.

Remarks:

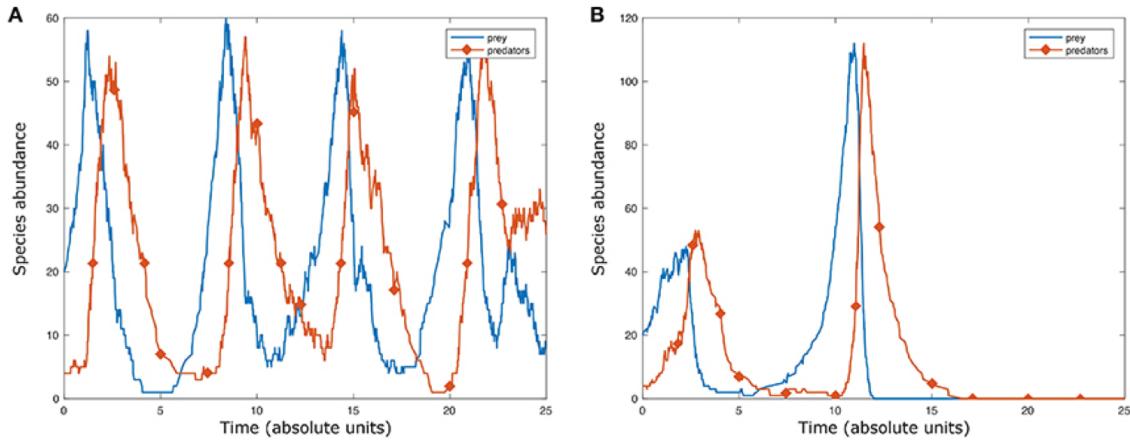


Figure 7.8: Lotka-Volterra stochastic simulation results. In B we witness preys and predators extinction, it is the output of a simulation performed with the same model and parameters as A.

- we did a lot of computations
- s_1 , the initial set of parameters, had values at different orders of magnitude. We really do not know if we are doing well or not.

7.5 Stochastic methods for parameter estimation

Stochastic methods are often used when we cannot compute the gradient. With the same parameters, stochastic methods can produce dramatically different results.

Lotka-Volterra stochastic simulation results are reported in Figure 7.8- In B we witness preys and predators extinction, it is the output of a simulation performed with the same model and parameters as A.

Instead of following the gradient, we collect information in a manner resembling natural selection. Monte Carlo Methods are dated around 1949, the name comes from casinos (recalls concept of luck). In order to use MCMC to do inference, Metropolis and Hastings developed a specific algorithm in 1970.

7.5.1 Markov Chain Monte Carlo (MCMC)

MCMC is a chain of events where the current state depends on the previous one and on the transition probability. If $x^{(i)}$ is a random variable (stochastic process) and it takes only discrete values $\{x_1, \dots, x_s\}$. Let $p(x)$ be the probability distribution of x . $x^{(i)}$ is a Markov Chain if:

$$p(x^{(i)} | x^{(i-1)}, \dots, x^{(1)}) = T(x^{(i)} | x^{(i-1)})$$

Simplest case: a MC is **homogenous** if $T(x^{(i)} | x^{(i-1)}) = T$, i.e. the transition matrix is constant.

If we run MCMC long enough, they will hopefully reach a stable point.

Example: 3 states and homogenous transition matrix

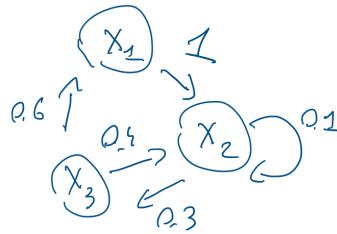


Figure 7.9: MCMC example

$$T = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0.1 & 0.9 \\ 0.6 & 0.4 & 0 \end{bmatrix}$$

MCMC example (Figure 7.9):

$$\pi_1 = (0.5 \quad 0.2 \quad 0.3)$$

The next probability of being in the three states is given by

$$\pi_1 \cdot T = (0.3 \cdot 0.6, \quad 0.5 + 0.02 + 0.12, \quad 0.18) = (0.18, \quad 0.64, \quad 0.18)$$

If we do this enough, we will always arrive to a fixed distribution, called invariant distribution \Rightarrow we want to build a Markov Chain whose invariant distribution is the distribution of our unknown parameters.

$$p(x) = \dots = \begin{pmatrix} 0.2213 \\ 0.4098 \\ 0.3689 \end{pmatrix}^T$$

Where $p(x)$ is called **invariant distribution**.

A stochastic matrix is *irreducible* if its graph does not contain unconnected sub-graphs. If T is an irreducible transition matrix (+ aperiodic) \rightarrow the MC has an invariant distribution. We must connect probability distribution / values for the parameters with the model. There is a known function that we can use to do so.

Monte Carlo refers to a family of methods developed for **sampling**. In particular, we obtain samples of a certain i.i.d. random variables $\{x^{(i)}\}_{i>0}$ from a known density $p(X)$.

The samples can be used to “estimate / approximate” a target density / distribution. We exploit known distributions e.g. Normal, Poisson, ... to approximate our unknown distribution of interest.

Given enough samples, we can approximate p as:

$$p_N(x) = \frac{1}{N} \sum_{i=1}^N \delta_{x^{(i)}}(x)$$

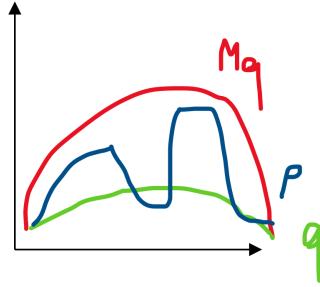


Figure 7.10: Example: bimodal distribution

with $\delta_{x^{(i)}}(x) = \begin{cases} 1, & x = x^{(i)} \\ 0, & \text{elsewhere} \end{cases}$ This is often used to approximate “hard” integrals. We can approximate an integral with a finite sum of values, which is obtained as:

$$I_N(f) = \frac{1}{N} \sum_{i=1}^N f(x^{(i)})$$

Here we are evaluating the function at some points. We can use the mean as an approximation of the integral. This equation converges to the real integral by the law of large numbers.

$$I_N(f) = \frac{1}{N} \sum_{i=1}^N f(x^{(i)}) \xrightarrow{N \rightarrow \infty} I(f) = \int_x f(x)p(x)dx$$

A probability is richer than the output of one least squares, we have information on the shape.

7.5.2 Sampling a distribution

Let p be a known probability distribution (up to a proportionality constant). We usually prefer to sample from a well-known distribution $q(x)$ s.t. $\exists M > 0$

$$p(x) \leq Mq(x)$$

We extract values from q if they are smaller than Mq ; each time we are collecting information on p collecting from q .

7.5.3 Rejection sampling algorithm

Set $i = 1$

REPEAT

 Sample $x^{(i)}$ from q and $u \in \mathcal{U}(0, 1)$

 IF $u < \frac{p(x^{(i)})}{Mq(X^i)}$ and $x^{(i)}$
 $i = i + 1$

 ELSE

 REJECT

If the point is in the area between p and Mq we still accept it; the further the ratio is from one, the smaller the chance of keeping the point.

At this point we are using a known distribution p ; we then gradually remove what we know in the following iterations.

7.5.4 Metropolis Hastings

Let X be our current point, q the proposal distribution and p the target distribution. p can be an unnormalized density ($\int p > 1$ but $\int p < \infty$). Ideally we want to know p , but if it is unknown we can still proceed. Let us call this function h (non negative and positive integral).

X^* is the new candidate point. The trick of MH algorithm is to avoid relying on probability, we use a function. We require info on p , but not a probability.

Metropolis ratio $r_M(x, x^*) = \frac{h(x^*)}{h(x)}$

Hastings ratio $r_H(x, x^*) = \frac{h(x^*) \cdot q(x|x^*)}{h(x) \cdot q(x^*|x)}$ From the distribution, we want to measure how likely the previous value is based on the current value. We are weighting our choices to likeliness.

7.5.4.1 MH algorithm

```

Guess  $x^{(i)}$ 
FOR  $i = 0$  to  $N - 1$ 
    Sample  $x^*$  from  $q(\cdot|x^{(i)})$  and  $u \in \mathcal{U}(0, 1)$ 
    IF  $u < \min\{1, r_H(x, x^*)\}$ 
         $x^{(i+1)} = x^{(*)}$ 
    ELSE
         $x^{(i+1)} = x^{(i)}$ 
    END
END

```

We sample from a proposal distribution and accept according to another function i.e. if it is more likely. If it is not more likely, we accept it with a certain chance.

MATLAB plot:

- right: histogram with the known distribution
- left: MCMC oscillating between 0 and 10, recapitulates the distribution

The procedure is really fast, takes less than a second. If instead of extracting u and v from random distribution with an index, the result is the same → “thanks MATLAB, it is not necessary to pre-locate anymore”

If we employ a Gaussian distribution, the result is still good but not as accurate as the previous one. We are adding complexity by introducing the variance; by choosing a different value we can improve the result. Pay attention to the fact that if we sample from a narrow distribution, we risk focusing only on one of the two points.

Everything we do has consequences!

7.5. STOCHASTIC METHODS FOR PARAMETER ESTIMATION

7.5.4.2 Visualization of MCMC

<http://chi-feng.github.io/mcmc-demo/app.html?algorithm=RandomWalkMH&target=banana> Green: accept, red: reject

Target distribution = standard

- GibbsSampling: collects points according to a certain direction from a starting point, it tries to rebuild a 2D Normal distribution.
- AdaptiveMH: sample from a starting mean and accept or reject new points.
- Random walk: more or less like MH. Even if the target distribution is not that difficult (bell shape), there are a lot of rejections initially.
- DE-MCMC-Z: produces vectors.

Target distribution = donut

- SVGO: stochastic vector gradient descent, intermediate between gradient and stochastic.
- EfficientNUTS (No-U-Turn samples): it creates many points, more complex but one of the best. In the end it will converge quite fast.
- RandomWalk: needs more time to converge with respect to standard distribution.

Target distribution = multimodal

- RandomWalk: three initial points, it proposes a random perturbation.
- AdaptiveMH: changes some of the parameters. Differently from the previous approach, the shape changes: instead of having a fixed search area, it evolves and adapts.

7.5.4.3 How to link data and MH

In LSQ, we used the function

$$f(\theta) = \frac{1}{2} \sum_{j=1}^m r_j^2(\theta) = \frac{1}{2} \sum_{j=1}^m (y_j - m_j(t_i, \theta))^2$$

We can weight our residuals for their uncertainty:

$$f_w(\theta) = \frac{1}{2} \sum_{j=1}^m \frac{r_j^2(\theta)}{\vartheta_j^2}$$

ϑ_j = (for example) the standard deviation of that measured point.

We can use as function to link the parameters and the output, and be non-negative: [where Y is the vector of our observations]

$$L(\theta|Y) = \exp(-f_w(\theta)) \geq 0$$

We can use this as h in the MH algorithm.

Metropolis ratio:

$$r_H(\theta^*, \theta) = \frac{L(\theta^*)}{L(\theta)} = \frac{e^{-f_w(\theta^*)}}{e^{-f_w(\theta)}} = \exp(-f_w(\theta^*) + f_w(\theta))$$

So since $f_w(\theta) \geq 0$ we have that if $f_w(\theta^*) > f_w(\theta) \Rightarrow r_H > 1$, we ACCEPT. Otherwise we accept with a certain probability. This kind of function can be used to link the new parameters with data. We can work with log-likelihood also here, we just look at $f_w(\theta^*)$ and $f_w(\theta)$.

7.5.5 Random walk MCMC

Let us assume θ^* is sampled from $\mathcal{N}(0, \mathcal{C}) + \theta = \mathcal{N}(\theta, \mathcal{C})$

We add a perturbation with \mathcal{C} , a known covariance matrix. \mathcal{C} can be fixed or adapted along the iterations.

From the initial point we have a new candidate according to a multivariate normal distribution; if the candidate is accepted, we will then restart evaluation from it. We are collecting some information allowing us to shape the target distribution.

7.5.5.1 Algorithm RW-MCMC (C known)

Initialize a matrix D_θ and a vector V_L

Randomly generate θ_1

Compute $L(\theta_1) = L_1$

For $i = 1 : N$

sample $Z \sim N(D, \mathcal{C})$

compute $\theta_2 = \theta_1 + Z$

compute $L_2 = L(\theta_2)$

compute ratio = $\frac{L_1}{L_2}$

sample $u \sim \mathcal{U}(0, 1)$

IF $u <$ ratio

$L_1 = L_2$

$\theta_1 = \theta_2$

END

IF $i >$ warm-up

$D_\theta = [D_\theta; \theta_1]$

$V_L = [V_L; L_1]$

END

END

We want to find a good accept-reject tradeoff to reach a satisfactory convergence.

Pros

- the object function is evaluated once per iteration
- the target distribution can be built from the samples
- we only need the last point to restart
- we can collect info on the model: variability on the output + sensitivity on parameters
- random selection helps us to avoid local minima

Cons

- convergence may be slow

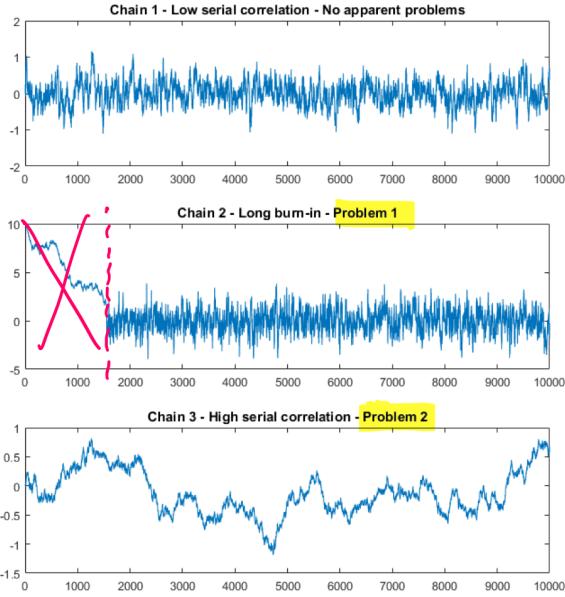


Figure 7.11: Diagnostic 1

- sampling distribution may affect the results
- each MCML cannot be parallelized
- burn-time
- diagnostics are heuristics

7.5.5.2 Diagnostics

We can exploit diagnostics to check if the parameters are good and understand whether we are done or not.

1. chain 1: expected MCMC plot
2. chain 2: we require a longer burn-in, we have not reached the target distribution
3. chain 3: we do not have enough information, the number of iterations is too small

The desired output of MCMC should look like the following plots:

Another more analytical approach is **sample split**. If we split the plot in different regions, do they have the same mean? Do we observe consistency? In chain 2 we need longer warm up, in 3 we need more samples.

Differently from gradient methods, here things are a bit more hard to interpret. We know that eventually we will reach oscillations around the global optimum, but we have no guarantee.

Diagnostics are based on the observation of the results, so they might be biased by our belief and they do not provide an easy way to read “certificate” of convergence.

Another approach may be run more MCMC in parallel and see if they all converge to the same distribution. However, it is again not a certificate of convergence to the global optimum.

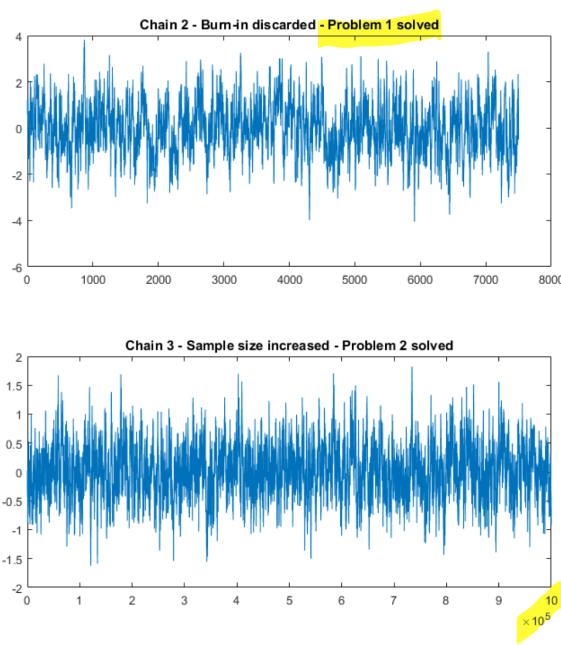


Figure 7.12: Diagnostic 2

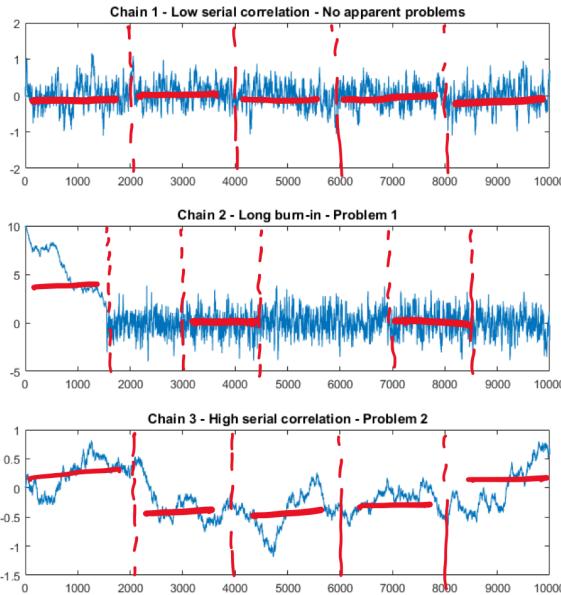


Figure 7.13: Diagnostic 3

Last observation: constraints and bounds can be included easily in the proposal distribution or in the likelihood.

7.6 Heuristics and the genetic algorithm

“Heuristics is a fancy name for trial-and-error”.

Heuristics mimic natural selection i.e. follow nature inspired procedures. At the growing of computational power, they become feasible ways to solve optimization problems. There are no warranties on the exactness of the solutions, but often times the results are of high quality. In addition, heuristic algorithms are easy to implement, are general and can include *constraints* (even complex ones).

Example: timetable for plane departures. Deciding when a plane lands is not only a function of flight time, we should take into account delays, passengers, luggages, crew, ... → constraints. In biological problems we can include relationship among variables which should be satisfied, allowing high flexibility.

There are many famous heuristic algorithms:

- simulated annealing: used in physics, match thermal dispersion
- ant colonies: ants are able to solve many problems e.g. supply chain
- covariance matrix adaptation evolution strategy: performs similarly to adaptive MH algorithm

All these methods have something in common: EVOLUTION STRATEGY.

For observing evolution, we require to have a **population** of candidate solutions - not only by this method, e.g. MCMC. We then select candidates according to their **fitness function** (objective function). The changes in the populations occur as results of variations on the current population.

7.6.1 The genetic algorithm

The genetic algorithm (GA) is a family of evolutionary strategies, introduced in 1975 by John Holland. It encodes tentative solutions in chromosomal like structures. Evolution occurs as reproductive opportunities for the fittest. External variation is introduced through *mutations*.

Fundamental steps

- encoding of the chromosomes
- generation of an initial population
- fitness evaluation
- parents selection
- reproduction (crossover)
- mutation
- new population

The process is repeated from the new population to fitness evaluation. We need to understand how to encode our problem and how the selection of the mutation and reproduction are performed.

7.6.1.1 Chromosome encoding

Chromosome encoding is performed through bit strings; we have a long entity θ (chromosome) divided into sections (genes).

7.6.1.2 Generation of an initial population

Analogously to the starting points of a multi-start:

- Random
- Latin hypercube
- Orthogonal sampling

7.6.1.3 Fitness evaluation

The objective function for the current population could be picked from known functions e.g. sum of squares, likelihood or more general formulations. As long as there is a connection between the fitness number and candidate selection, the function is fine. MCMC was using one candidate at a time at each iteration, while gradient methods were computing the gradient using information from integration. In this case, the size of the population will determine the number of calls.

7.6.1.4 Parent selection

The parents can be selected through:

- threshold based selection - select best k parameters
- random based selection
 - Example (similar to Gillespie, we use fitness instead of the propensity):
From f^1, \dots, f^N compute $\sum_{i=1}^N f_i = f_0$
Generate random number $j \sim \mathcal{U}(0, 1)$
Select the smallest k such that $\sum_{i=1}^k f_i > j f_0$
Clone θ^k in an intermediate population

“Roulette selection”, the area of a circle is covered by each chromosome fitness proportionally.
The idea is to spin the wheel and select the chromosome where it stops.

7.6.1.5 Reproduction

From the intermediate population we randomly select two individuals u, v and a gene for cross over t . We recombine parent chromosomes and add new offspring to the new population. This procedure is only inheriting information from the previous generation, we are missing mutations.

7.6.1.6 Mutation

The offspring may or may not mutate according to a certain probability. We denote p the probability that a gene of the new offspring mutates.

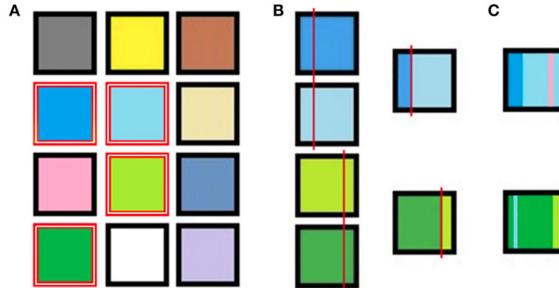


Figure 7.14: From Reali et al 2017 - GA procedure example

Input: a fitness function c that measures the goodness of the fit, for example (Equation 5); the population size N ; the rate of mutation σ ; the maximum number of generations G .

Output: the best candidate solution \tilde{p} after G generations.

```

1 Map the parameters into strings of length  $l$ ;
2 Generate an initial population of strings  $P = \{p_1, \dots, p_N\}$ ;
3 for  $G$  times do
4    $P' = \emptyset$ ;
5   Compute  $f_i = c(p_i)$ ,  $i = 1, \dots, N$  and  $f_0 = \sum_{i=1}^N f_i$ ;
6   for  $N$  times do
7     Generate a random number  $j \sim U(0, 1)$ ;
8     Determine the smallest integer  $k$  such that
9        $\sum_{i=1}^k f_i > jf_0$ ;
10    Update  $P' = P_k \cup P'$ ;
11  end
12  for  $N$  times do
13    Generate two integer random numbers
         $m, n \sim U(1, N)$ ;
    Select  $p_m, p_n \in P'$ ;
    Generate an integer random number  $t \sim U(1, l)$ ;
     $\tilde{p} = \{p_m[1 : t], p_n[t + 1 : l]\}$ ;
    for  $i = 1, \dots, l$  do
      | with probability  $\sigma$  randomly variate  $\tilde{p}[i]$ ;
    end
    Update  $P = \tilde{p} \cup P$ ;
12 end
13 Determine the best solution  $\tilde{p}$  such that  $c(\tilde{p}) = \min_{p \in P} c(p)$ ;

```

Algorithm 3: A simple Genetic Algorithm.

Figure 7.15: From Reali et al 2017 - GA pseudocode

7.6.2 Genetic algorithm pseudocode

Observations on specifications:

1. how many times do we go? Here we usually start by defining a number of generations
2. size of each population, use function to decide

The cost function is as general as possible. GA is sometimes used for hyperparameters tuning e.g. we can train a NN inside the algorithm. This is not feasible with Markov Chains or gradient methods.

However, we do not know whether the new generation is better than the previous one.

7.6.2.1 Cons

It is quite computationally demanding, as for N times we compute the likelihood/cost/fitness just for selecting new parents. Next, we are not directly getting direction, the reduction of the fitness function is not driven by the dimension of the population. Close to the optimum it converges slowly.

7.6.2.2 Pros

Each one of the computations can be parallelized. Some might argue that it can be used for everything. It is very general and obtains good results. f can vary sometimes; the algorithm can use an obj function without the constraints, that can be added as penalties after some generations.