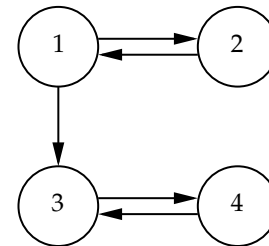


Influence of update schemes on boolean networks

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Abstract—In this paper we will introduce boolean networks (BN) and their relevance to gene regulatory networks (GRN). We will have a closer look on update schemes. Specifically, synchronous, sequential and asynchronous update schemes and their effect on the behavior of BN and GRN respectively.

will be change once introduction and conclusion are done



1 INTRODUCTION

Possible points to mention here:

- Explain shortly gene regulatory networks (GRN)
- Explain why boolean networks are used to model GRN
- Maybe mention history of boolean networks
- Set the focus to the update scheme as it seems to be rarely covered in the field of GRNs
- Possible open question about which update scheme might be best to model GRNs. Answer to this must follow in the conclusion

$$\begin{aligned}f_1 &= \neg x_2 \\f_2 &= x_1 \\f_3 &= x_1 \oplus x_4 \\f_4 &= x_3\end{aligned}$$

Fig. 1. Example of a boolean network with four nodes. Each vertex indicates that a node is part of the update function of the other node. For instance x_1 is part of f_2 and f_3 .

2 BOOLEAN NETWORKS

A boolean network consists of nodes $x_i(t)$ that have a boolean state, either 0 or 1, at a point in time t . Each node has a corresponding update function $x_i(t+1) = f_i(x_1(t), x_2(t), \dots, x_n(t))$ expressing the new state of $x_i(t+1)$. The state of the boolean network can be describe as a boolean number $x_1x_2 \dots x_n$ where each node is replaced with the corresponding state.

Consider the boolean network shown in fig. 1. Assume the current state is 0011, meaning that x_1, x_2 are 0 and x_3, x_4 are 1. The next state when applying the update function all at once is 1011. Updating the network multiple times creates a trajectory, which is the sequence of the states starting from the initial state. With our example, the trajectory is $0011 \rightarrow 1011 \rightarrow 1101 \rightarrow 0100 \rightarrow \dots$ Each trajectory in a reasonably small boolean network eventually reaches one of two scenarios. Either it falls into a state, called attractor, that doesn't change when updated, or it falls into a cycle of states. In the example, there are 2 cycles of length 8 visible in fig. 2.

currently feels to short. once introduction is implemented, create a better transition/section 2 introduction. Also introduce robustness!

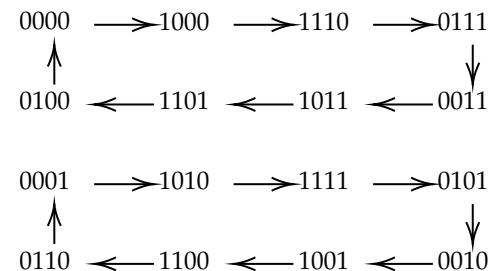


Fig. 2. State graph of the boolean network shown in fig. 1 using synchronous update scheme.

3 UPDATE SCHEMES

Explain different update schemes including characteristics for behavior especially chaotic behavior. These will mostly focus on boolean networks only. Maybe mention of use-cases for each update scheme.

update this text.. (or remove it)

3.1 Synchronous scheme

In section 2, we have used the synchronous update scheme to introduce the workings of boolean networks. This scheme

assumes that each update function takes the exact same amount of time and executes at the same time, meaning regardless of the outcome of the first function, any other function will have the same result. Updating the network with this method is on one side quite simple, deterministic and doesn't require a lot of computing power in order to simulate larger networks, as each state of the network results in exactly one updated state. In regards to gene regulatory networks, this is an oversimplification as normal GRNs never execute fully synchronously.

add more context and information about grn and their effects, split text into logical paragraphs

3.2 Sequential scheme

When using the sequential update scheme, the update cycle processes each after another in a fixed order. For example take the sequence x_1, x_2, x_3, x_4 . Updating the state 0000 means first using f_1 which results in an intermediate state 1000, then using f_2 , then f_3 and lastly f_4 . This will lead to 0000 $\rightarrow$ 1111, a different state as when using the synchronous update scheme. In fact the whole state graph changes depending on the update scheme used, namely every initial state will fall into a single 4-state cycle being 0000 $\rightarrow$ 1111 $\rightarrow$ 0011 $\rightarrow$ 1100 $\rightarrow$ 0000, see ??.

refer to synchronous by computing new functions that can be run synchronously with the same outcome as sequential with the current functions

3.3 Block-sequential scheme

mix of synchronous and sequential. predefined blocks update sequential, inside a block the update follows the synchronous scheme

3.4 Probabilistic scheme

The Probabilistic update scheme is a synchronous scheme in terms of executing the functions, however, there is no longer only one function per node. Instead you can have multiple functions per node with each a fixed probability. This introduces some noise into the system and can lead to more realistic simulations. In order to show it using the example from fig. 1, we need to define a new set of functions, which will only be used in this section.

PLACEHOLDER

refer to [1] and potentially add figure 2 from that paper

3.5 Asynchronous deterministic

one node is updated per tick following a specific sequence

create introduction, conclusion/transition to the next scheme for each scheme

4 RELEVANCE FOR GENE REGULATORY NETWORKS

Tie the update schemes and their different outcomes or behavior to GRN.

Emphasizing the drawbacks of asynchronous models when applied to GRN e.g. it takes way too long to update a GRN using asynchronous deterministic for it to have an effect; assuming that one update takes a few minutes, when the whole process can take days to complete.[1]

5 CONCLUSION

Not yet included: robustness! might be covered for each update scheme individually.

References: [1][2][3][4][5]

currently not really using references. i need to go over everything again and add the references at the right spots and even mention them explicitly in sentences for further context.

DON'T FORGET THE 2 MINUTE SLIDES!!!

REFERENCES

- [1] Julian D Schwab, Silke D Kühlwein, Nensi Ikonomi, Michael Kühl, and Hans A Kestler. Concepts in boolean network modeling: What do they all mean? *Computational and structural biotechnology journal*, 18:571–582, 2020.
- [2] Julio Aracena, Eric Goles, Andrés Moreira, and Luis Salinas. On the robustness of update schedules in boolean networks. *Biosystems*, 97(1):1–8, 2009.
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