On plant roots logical gates

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Abstract

Theoretical constructs of logical gates implemented with plant roots are morphological computing asynchronous devices. Values of Boolean variables are represented by plant roots. A presence of a plant root at a given site symbolises the logical TRUE, an absence the logical FALSE. Logical functions are calculated via interaction between roots. Two types of two-inputs-two-outputs gates are proposed: a gate $\langle x, y\rangle \rightarrow \langle xy, x+y\rangle$ where root apexes are guided by gravity and a gate $\langle x, y\rangle \rightarrow \langle \overline{x}y, x\rangle$ where root apexes are guided by humidity. We propose a design of binary half-adder based on the gates.

Keywords: plant roots, logical gates, unconventional computing

1. Introduction

A collision-based computation, emerged from Fredkin-Toffoli conservative logic [17], employs mobile compact finite patterns, which implement computation while interacting with each [1]. Information values (e.g. truth values of logical variables) are given by either absence or presence of the localisations or other parameters of the localisations. These localisations travel in space and perform computation when they collide with each other. Thus the localisations undergo transformations, they change velocities, form bound state sand annihilate or fuse when they interact with other localisations. Information values of localisations are transformed as a result of collision and thus a computation is implemented.

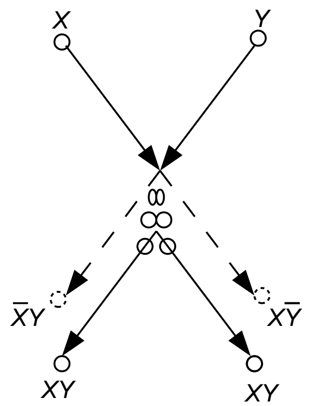


Figure 1: Margolus gate: collision between soft balls.

The concept of the collision-based logical gates is best illustrated using a gate based on collision between two soft balls, namely the Margolus gate [22], shown in Fig. 1. Logical value $x = 1$ is given by a ball presented in input trajectory marked x, and $x = 0$ by the absence of the ball in the input trajectory x; the same applies to $y = 1$ and $y = 0$, respectively. When the two balls, approaching the collision gate along paths x and y collide, they compress but then spring back and reflect. As a result, the balls come out along the paths marked xy. If only one ball approaches the gate, that is for inputs $x = 1$ and $y = 0$ or $x = 0$ and $y = 1$, the balls exit the gate via path $x\overline{y}$ (for input $x = 1$ and $y = 0$) or $\overline{x}y$ (for input $x = 0$ and $y = 1$).

The designed experimental prototypes of logical gates, circuits and binary adders employ interaction of wave-fragments in light-sensitive Belousov-Zhabotinsky media [15], swarms of soldier crabs [20], growing lamellipodia of slime mould Physarum polycephalum [33, 3], crystallisation patterns in 'hot ice' [2], peristaltic waves in protoplasmic tubes [5], and jet streams in fluidic devices [28], or as competing patterns propagation in channels of communication with a Life-like CA [23]. These prototypes suffer from various disadvantages. For example, wave-fragments in Belousov-Zhabotinsky medium are short-living and difficult to control (they are prone to expansion or contraction), slime mould protoplasmic tubes lack stability and exhibit tendency to uncontrolled branching, swarms of soldier crabs might behave chaotically and the corresponding gate requires a bulky setup. Another problem is synchronisation. When Boolean values are represented by localised, finite size, patterns — the accuracy of synchronisation depends on the size of the patterns. For example, if two wave-fragments in Belousov-Zhabotinsky medium collide not 'perfectly' but with an offset more than a half-wave length, then the output of the gate will be ineligible. Thus we aimed to find physical or biological analogs where signals are well controlled and stable and large errors in synchronisation are allowed.

Plant roots could offer us a viable alternative. Plant roots could perform a computation by growing and shaping their morphology in the fields of attractants and repellents [10, 11, 37] which represent data configurations, as well with wave-like propagation of information along the root bodies via plant-synapse networks [13] and competition and entrainment of oscillations in their bodies [12]. In most of the aforementioned cases, the corresponding computation results are represented by the topology of root apex trajectories which are preserved in a physical location of the root. The computing circuits proposed receive input signals on both inputs at the same time, synchronously, and the signals are 'desynchronised' en route due to different lengths of input channels.

2. Gravity gates

We propose gates made of channels. The roots grow inside the channels. The roots apexes navigate along the channel using mechanical, acoustic [18] and visual [27, 9] means. Root apexes exhibit a positive gravitropism [16, 29, 8, 7, 24]. Thus being placed in a geometrically constraint environment of a channel, a root grows along the same direction as the gravity force.

Consider an interaction gate with two inputs x and y and three outputs p, q, r (Fig. 2a). If channels would be wide enough to accommodate several routes then the routes would join each other following along the channel q, due to the roots swarming behaviour [14]. We assume a channel can accommodate only one root. Root apexes are guided by gravity. A root entering channel y propagates till the junction, then follows the gravity and moves along channel q (Fig. 2b). A root entering channel x also propagates along channel q (Fig. 2c).

What happens when two roots enter channels x and y at the sametime? Assuming roots' apexes reach the junction precisely at the same time they might reflect into lateral channels because two roots at once can not fit in the vertical channel q (Fig. 2c). That is an ideal

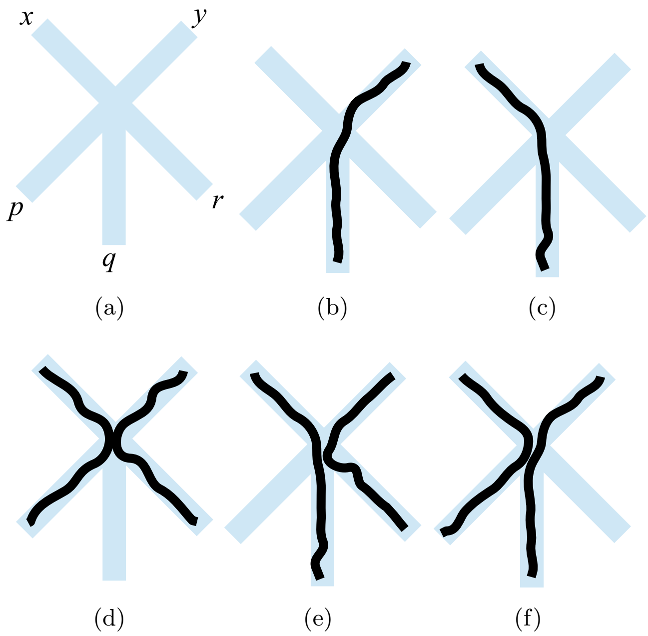


Figure 2: Gravity gate. Plant root logical gate. Only gravitropism is taken into account. Two roots can not fit in one channel. (a) Scheme: input channels are x and y, output channels are p, q, r. (b) $x = 0$, $y = 1$. (c) $x = 1$, $y = 0$. (d) $x = 1$, $y = 1$, apexes arrive at the junction at the same time. (e) $x = 1$, $y = 1$, apex x arrives at the junction earlier than apex y. (f) $x = 1$, $y = 1$, apex y arrives at the junction earlier than apex x.

Table 1: Operations implemented by the gravity gate (Fig. 3).

x	y	$x+y$	xy	Interaction of roots
0	0	0	0	no roots entered input channels x and y
1	0	1	0	root propagated via channel x to q
0	1	1	0	root propagated via channel y to q
1	1	1	1	root x is blocked by root y and therefore deflected to channel p

situation. Unlikely this will ever happen because there are no two seeds which produce roots with exactly the same biochemical and physiological parameters.

In reality one of the roots is faster or stronger. The stronger root pushes its way into the channel q while contender is left to deviate into the later channel. This is illustrated in Figs. 2ef. If root x wins its way into the channel q then root y grows into the channel r. Vice verse, if the root y is quicker to get into channel q then root x moves into the channel p. Assuming presence of a root in channel z symbolises logical truth: $z = 1$, and absence logical false: $z = 0$, the gate in Fig. 2 computes the following Boolean functions: $p = r = xy$ and $q = x\overline{y} + \overline{x}y + xy = x + y$, where $\overline{x}$ indicates the NOT signal of x and the same applies for $\overline{y}$ in correspondence to y, respectively. However, such a gate is not cascadable because — due to unpredictability of the competition between the apexes for the channel q — we never know where signal xy appears: either on channel p or on channel r.

To achieve a certainty we should allow one — specified a priori — root to reach the junction early. This is how we came up with the gate shown in Fig. 3a.

A channel segment a — from entry of the input channel x to the junction j — is longer than segment b — from the input to y to the junction. If a root is present only in input x, $x = 1$, it grows along a, reaches the junction and then propagates along d (Fig. 3b). If a root is present in input y, $y = 1$, it grows along b and continues along d (Fig. 3c). If roots are present in both

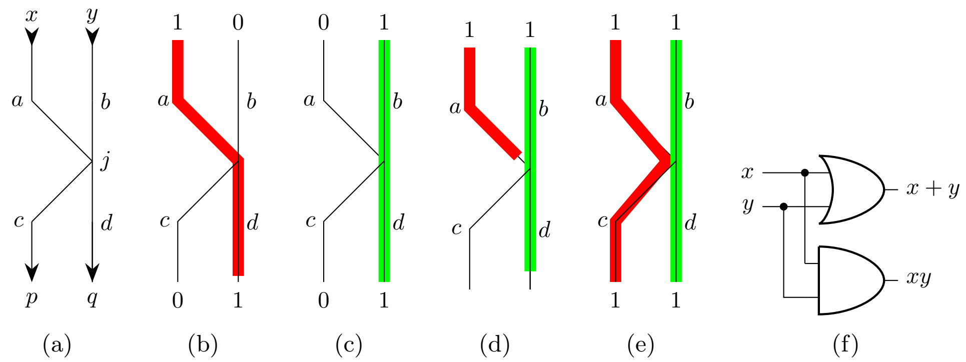


Figure 3: Gravity gate with two inputs and two outputs. (a) Scheme of the gate, the basic AND gate, i.e. $p = xy$ and the basic OR gate, i.e. $q = x + y$. In subfigures (bcde) the development of gate is provided. (b) Root enters input channel x only, $x = 1$ and $y = 0$. (c) Root enters input channel y only, $x = 0$ and $y = 1$. (d) and (e) Roots enter both input channels x and y, $x = 1$ and $y = 1$, at different time steps: (d) Time moment $t = |b| + \sqrt{|a|} - 0.2$, where $|a|$ and $|b|$ are lengths of channels a and b. (e) final state. (f) Equivalent logic gates design, namely AND and OR gates. Coloured inputs symbolise channels occupied by roots. Red and green colour are only here to show how roots originated at different inputs interact.

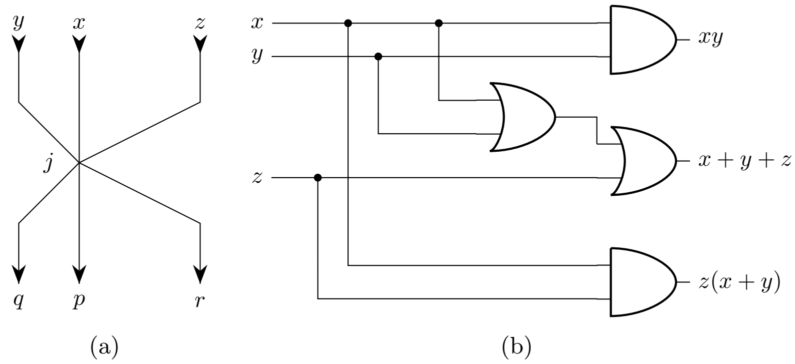


Figure 4: (a) Three-inputs-three-outputs gravity gate: $q = xy$ and $p = x + y + z$ and $r = z(x + y)$ and (b) its equivalent logical scheme.

inputs, $x = 1$ and $y = 1$, the y-root occupies the junction well before the x-root reaches the junction (Fig. 3d). Thus the y-root grows along d while x-root reflects into channel c (Fig. 3e). The operations are summarised in Tab. 1. The gate realises xy on one output and $x + y$ on another output; an equivalent logic gates design is shown in (Fig. 3f) in correspondence to the classic universal set of Boolean gates, namely AND and OR and NOT, implemented here with the same medium. It should be noticed that universal set of gates is a set of gates such that every Boolean function can be implemented with gates in this set. The gate allows for some asynchronicity. It does not matter for how long signal x is delayed, if it enters the circuit at the same time as or any time later than signal y the gate will produce desirable results.

The gravity gate $\langle x, y \rangle \to \langle xy, x+y \rangle$ (Fig. 3) can be extended into three-inputs-three outputs gate shown in Fig. 4a. The lengths of input channels are selected so that x-root reaches the junction earlier than y-root, and y-root reaches the junction earlier than z-root. Path along channel x to junction j is shorter than path along channel y to junction j. Path along channel y to junction j is shorter than path along channel z to junction j.

A root appears in the output channel p if a root grows at least in one of the input channels x, y or z, respectively. A root appears in the output channel q if roots are initiated in input channels x and y. A root appears in output r only if roots grow in channels x and z, or in

Table 2: Operations implemented by the three-input-three-output gravity gate (Fig. 4).

x	y	z	$x+y+z$	xy	$z(x+y)$	Interaction of roots
0	0	0	0	0	0	no roots enter input channels
0	0	1	1	0	0	root grows in channel z and exits via channel p
0	1	0	1	0	0	root grows in y and exits into p
0	1	1	1	0	1	root grows in y and enters p, while root in z is reflected into r
1	0	0	1	0	0	root grows in x and exits into p
1	0	1	1	0	1	root grows in x and exits into p and root in z is reflected into r
1	1	0	1	1	0	root grows in x and exits into p and root in y is reflected into q
1	1	1	1	1	1	root grows in x and exits into p, root in y and z are reflected one after the other, i.e. root in y is reflected into q, and root in z is reflected into r

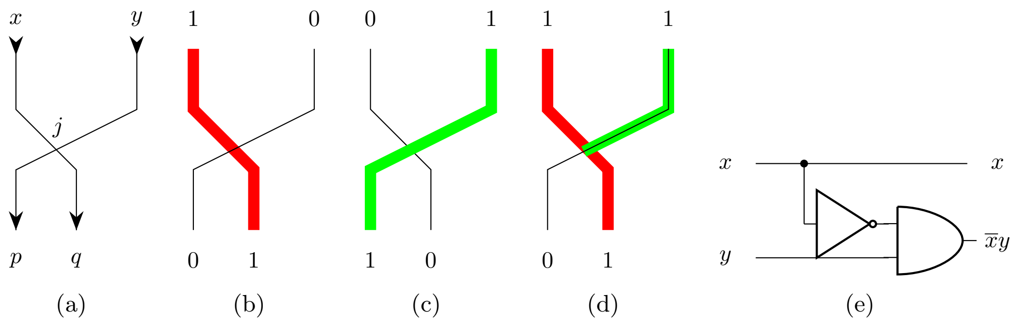


Figure 5: (a) Scheme of humidity gate with two inputs x and y and two outputs p send q: $p = \overline{x}y$ and $q = x$. (b) $x = 1$ and $y = 0$. (c) $x = 0$ and $y = 1$. (d) $x = 1$ and $y = 1$. (e) Equivalent logic scheme.

channels y and z. This gate realises Boolean functions $q = xy$, $p = x + y + z$, and $r = z(x + y)$ (Fig. 4b). Operations implemented by the gate are explained in Tab. 2.

3. Attraction gates

Root apexes are attracted to humidity [10] and a range of chemical compounds [31, 36, 19, 6, 32, 37]. A root propagates towards the domain with highest concentration of attractants. The root minimises energy during its growth: it does not change its velocity vector if environmental conditions stay the same. This is a distant analog of inertia.

Assume attractants are applied at the exits of channels p and q (Fig. 5a). When an apex of the root growing along channel x reaches a junction between channels, the apex continues (due to energy minimisation) its growth into the channel q if this channel is not occupied by other root (Fig. 5b). A root in input channel y grows through the junction into the output channel p (Fig. 5c).

The gate Fig. 5a has such a geometry that a path along channel x to junction j is shorter than a path along channel y to the junction j. Therefore, a root growing in channel x propagates through the junction into channel q before root starting in channel y reaches the junction. When both roots are initiated in the input channels the x-root appears in the output q but the y-root is blocked by the x-root from propagating into the channel p: no signal appears at the output p (Fig. 5d). This gate realises functions $p = \overline{x}y$ and $q = x$ (Fig. 5e). If y is always 1 the gate produces a signal and its negation at the same time.

Two attraction gates Fig. 5a can be cascaded into a circuit to implement a one-bit half-adder, with additional output, as shown in Fig. 6a. We assume the planar gate is lying flat and sources of attractants are provided near exits of output channels p, q and r. The half-adder is realised on inputs $p = x \oplus y$ (sum) and $r = xy$ (carry); the circuit has also a 'bonus' output $q = x + y$ (Fig. 6e). The circuits work as follows:

- Inputs $x = 1$ and $y = 0$: Two roots are initiated in channels marked x in Fig. 6a; one root propagates to junction j_1 to junction j_3 and exits in channel q; another root propagates to junction j_4 to junction j_2 and into channel p (Fig. 6b).

- Inputs $x = 0$ and $y = 1$: Two roots are initiated in channels marked y in Fig. 6a; one root propagates to junction j_1 then to junction j_2 and exits at channel p; another root propagates to junction j_4 then to junction j_3 then into channel q (Fig. 6c).

- Inputs $x = 1$ and $y = 1$: Roots are initiated in all four input channels. The root initiated in the northern channel x propagates towards exit q. This root blocks propagation of the root initiated in the southern channel y, therefore the root from the southern channel x exits the circuit via the channel r. The root growing in the northern channel x blocks propagation of the root initiated in the norther channel y, therefore no roots appear in the output p (Fig. 6d).

4. Discussion

Following the theoretical analysis of the proposed plant root gates, on-going experiments have been performed in the laboratory. A gate is printed in PLA, channels in the template were filled with 2% Phytagel (Sigma Aldrich). In the example illustrated onion seeds are placed in input channels x and y to implement input $x = 1$ and $y = 1$ (Fig. 7a). The template was partly covered, to keep roots away from light, and kept in a horizontal position in room temperature, humidity c. 60%. Two scenarios are illustrated. In Fig. 7b roots propagate along the channels and the y-root is reflected into channel b, while growth of the x-root is suppressed. This particular situation might resemble us scenario shown in Fig. 2d, especially of x-root deflected into channel a. In scenario shown in Fig. 7c a root propagation along channel x into channel b blocks a root propagation along channel y. In this particular scenario channel a can be considered as representing $\overline{x}y$. As seen from just two examples, despite apparent simplicity of the gates, experimental implementation is far from trivial. Substantial efforts would be required to precisely control propagation of root apexes and their interaction.

To have a more clear view for estimating the probabilities of anticipated behaviours like the ones introduces earlier in our analysis, various and numerous experiments should be performed indicating the role of seeds, patterns, environment, and many biochemical and physiological parameters. It should be mentioned that for the time being, such experiments are costly in matter of time; in general, 10–20 days are requested to depict the plant roots growth after seeds' germination. However, in such a way, we are expecting to include all the stimuli key-parameters that are needed to be clarified so as to secure the pattern recognition of the possible plant gates evolution.

As a future work and when such prototypes, like the ones introduced earlier in the Section, are made in also smaller time intervals they will lay a foundation for a research focused on developing computing architectures from plants, combining bio-electronics, unconventional computing, advanced functional materials, plant biology, robotics. The paper addressed new trends in computing, especially bio- and nature-inspired by encompassing key aspects of information processing in living plants and adaptation of plants processing structure. The proposed research is tailored to future emerging challenges in living technologies and unconventional computing in

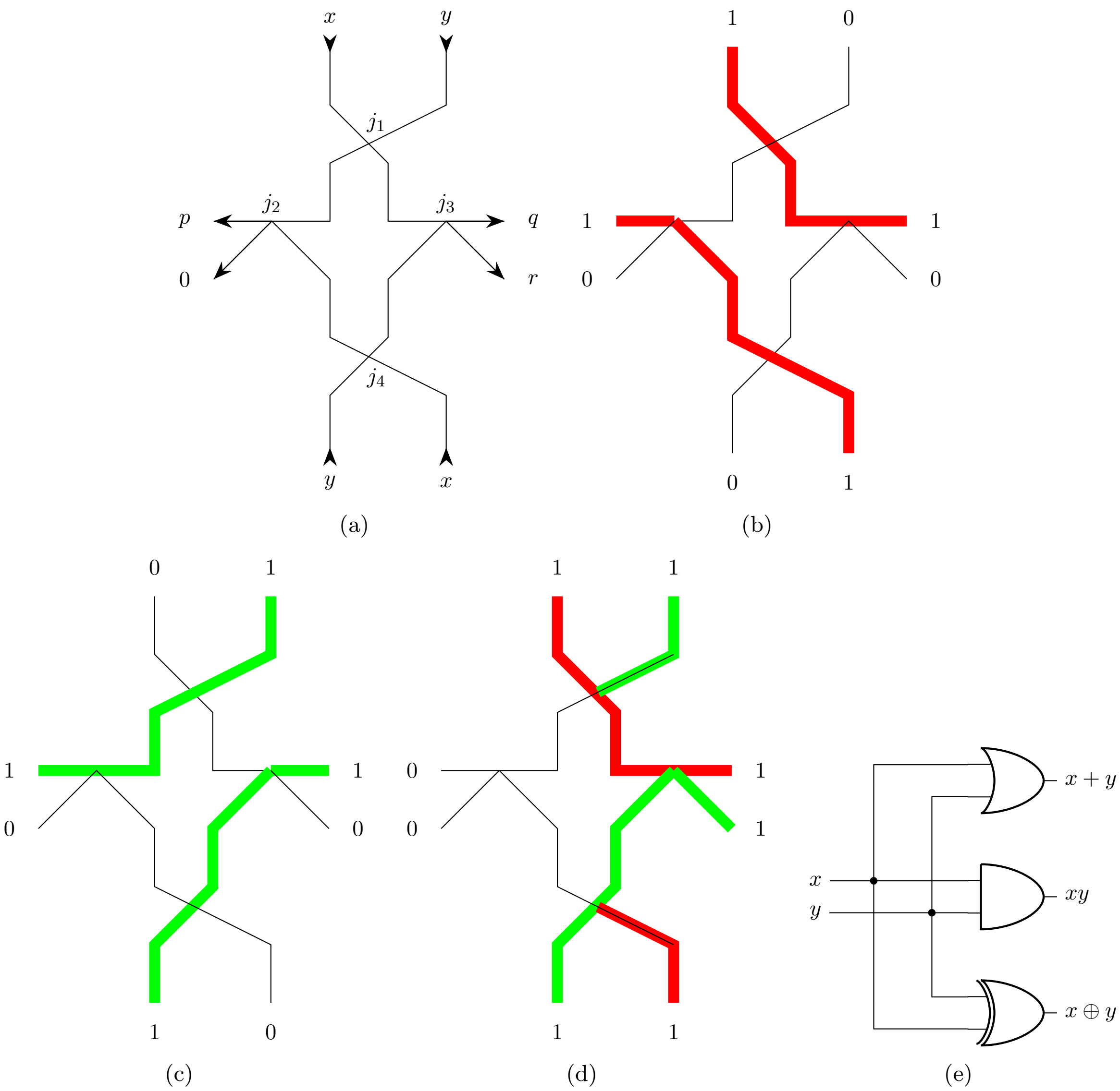
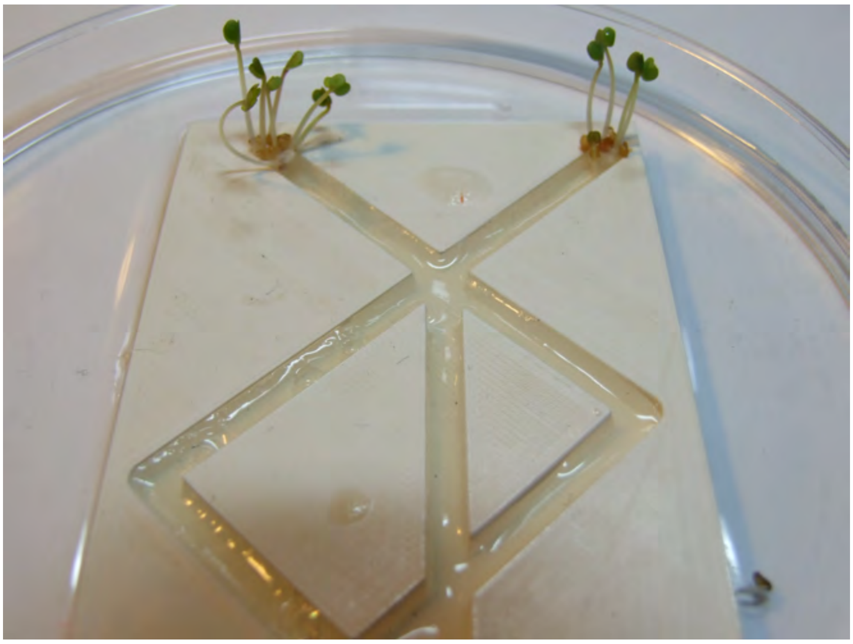
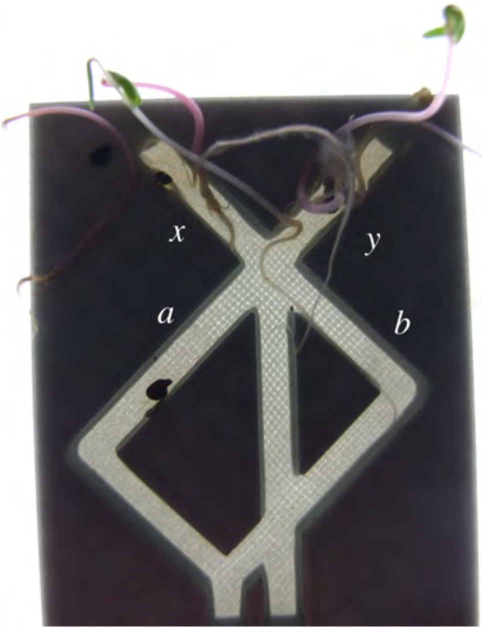


Figure 6: A half-adder made of two humidity gates. (a) Scheme of the circuit, $p = x \oplus y$, $q = x + y$, $r = xy$. (b) $x = 1$ and $y = 0$. (c) $x = 0$ and $y = 1$. (d) $x = 1$ and y. (e) Equivalent logic gates design.



(a)



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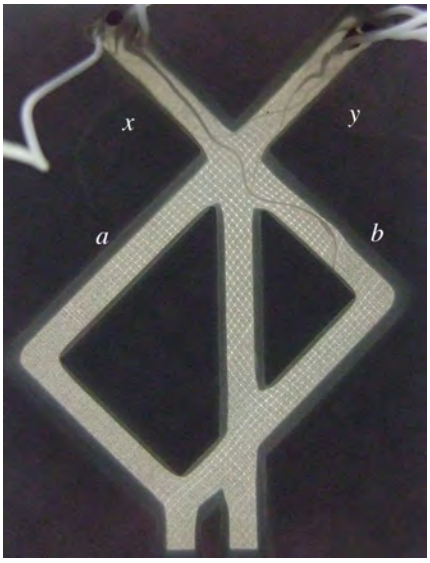

(c)

Figure 7: Examples of possible experimental implementation of the introduced plant root gates. (a) Experimental setup. Channels in the template were filled with 2% Phytagel (Sigma Aldrich). The template was kept in a horizontal position in room temperature, humidity c. 60%. (bc) Two scenarios of roots propagation and interaction.

highly interdisciplinary settings by developing new kinds of computational approaches in science. Towards this direction many questions are still open and seeking for answers either in regards to the already discussed computing part of other topics. For the latter someone could ask if there are any applications apart of making arithmetic-logical units with plant roots. The plant roots logical circuits can be embedded into decision making modules of root-inspired robots for soil exploration [25, 26, 21, 30]. On the other hand, the gates can be used as pre-programmed routing devices for automatic manufacturing of plant-based electronic devices, which will incorporate plant wires and memristors [4, 35, 34]. It is anticipating that more work in both theoretical and experimental basis will finally provide the foundations for the involvement of plants in different aspects of computation, like the one proposed in this paper.

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