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SOFT ROBOTICS
Volume 13, Number 6, 2026
Mary Ann Liebert, A Part of Sage
DOI: 10.1177/21695172261462701

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Soft Robotics

ORIGINAL ARTICLE

The Soft Circuits Toolkit: Teaching Mechano-Fluidic Logic for Soft Robotics

Catharina M. van Riet,[1,2] Shibo Zou,[1,3,4] Franciscus L.M. Delbressine,[2] Anke van Oosterhout,[2] and Johannes T.B. Overvelde[1,5]

Abstract

As soft robotics gains popularity, novel toolkits and educational systems for soft robotics are emerging. These endeavors focus mainly on teaching the programming or fabrication of soft robots, actuators, and sensors. However, as soft robotics moves toward electronics- and software-free control, it becomes essential to gain hands-on experience in soft fluidic circuit building and physical control. We bridge this gap in the educational landscape through the Soft Circuits Toolkit, a modular system of completely soft components that enables the creation and teaching of fluidic circuits, representing fluidic analogies of components such as resistors, capacitors, diodes, and transistors. The toolkit went through two design iterations and four user tests, which ultimately resulted in the toolkit presented in this article, consisting of 17 component types, a manual, and a companion website. User testing across various dimensions, including user experience, with technical university students ($N = 25$) indicates that our toolkit is engaging, easy to learn, and promotes problem-solving behaviors. Based on these results, we believe that our kit can support technical universities in teaching about fluidic circuit building and physical control of soft robotics. All fabrication files for this toolkit have been made available open source.

Keywords: toolkit, circuits, fluidic logic, soft robotics, physical control

Introduction

Physical control for soft robotics designs enables the development of fully soft robotic devices that are not dependent on electronics or software to function.[1–3] By moving the control from a central processor to the structure that makes up the soft robots, intelligence can be directly embodied[4,5] in the devices themselves. Removing the need for rigid and bulky computers to achieve autonomous behaviors is particularly effective in applications such as wearable devices that are in close or direct contact with the human body,[6,7] human–robot interaction,[8] shape-changing interfaces[9] and haptics,[10] biomedical devices,[11] and robots for extreme environments.[12] Focusing on fluidic control for soft pneumatic robots in such applications, fluidic circuits allow the embodiment of intelligence within the structure of the robot, by enabling, for example, self-regulation such as self-oscillation,[13,14] sequencing,[15,16] and responsiveness to the outside world.[17,18] Recent contributions have showcased platforms that enable the autorouting of complex fluidic circuits[19] and Fused Deposition Modeling (FDM) printing of soft robots with embedded fluidic logic.[20] Nevertheless, in the literature, many custom-made devices are presented with specific functionalities, which can be difficult to build and integrate together, as universal standards across the soft robotics field

[1] Autonomous Matter Department, AMOLF, Amsterdam, the Netherlands.
[2] Department of Industrial Design, Eindhoven University of Technology, Eindhoven, the Netherlands.
[3] Department of Biomechanical Engineering, Delft University of Technology, Delft, the Netherlands.
[4] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast, United Kingdom.
[5] Institute for Complex Molecular Systems and Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands.

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are lacking. As a result, for many designers, engineers, and novices in this field, it is still difficult to develop the mindset to prototype soft devices with physical control because this requires access to specialty equipment and materials as well as in-depth knowledge of circuit-building, pneumatics, and control,[21] making the barrier to entry to this field relatively high.

To lower the entry barrier to robotics design in general, educational toolkits abound for electronic circuit-building and programming,[22,23] as well as specialized kits for programming robots.[24–29] For soft robotics education specifically, fewer commercial (and therefore broadly available) toolkits exist. A few research projects are available for loan or purchase, such as FlowIO[30] and Programmable Air,[31] which offer microcontroller control over pneumatic power sources. Some pneumatic toolkits focus on the creation of inflatable structures[32–34] or the exploration of shape-changing interfaces[35] and modules.[9] Perhaps the most well-known resource in this field is the component-based Soft Robotics Toolkit,[36] an online resource with documentation and tutorials on how to fabricate soft actuators and sensors, as well as an electronic control unit for these. However, many of the above-mentioned examples[30–33,35,36] rely on a centralized control unit to control soft pneumatic devices. The central control unit typically inflates and deflates actuators through bulky pumps and valves. Any sensory feedback generated from human–robot interactions needs to go through this central control unit. Conversely, the embodied intelligence approach blurs the distinction between actuator, sensor, and controller,[4] as these can be combined into a single component. The fluidic relaxation oscillator,[14] for example, creates a pulsed pneumatic output that does not rely on an external control unit to regulate the oscillation. Although some kits offer an electronics-free design space, these either consist of partially rigid components[37] or they lack circuit-building implementation.[21] A completely soft toolkit that teaches fluidic logic circuitry would allow designers, engineers, and students to effectively learn the embodied intelligence philosophy, particularly regarding soft, compliant structures and the fluidic circuitry needed to integrate control and sensing in these structures.

To bridge this gap, here we present an educational toolkit for soft fluidic circuits, based on the modularity and functional behavior of electronic circuits. Our Soft Circuits Toolkit (Fig. 1) offers various soft pneumatic control, actuation, and sensing components that can be combined into fully fluidic circuits, thus facilitating soft robotics prototyping while also inspiring and teaching about soft robotic (pneumatic) circuits and the embodied intelligence mindset. To achieve these goals, we developed a standardized range of fully soft, pneumatic components, accompanied by a soft gripper and paper frog and bird (Fig. 1A). These components can be actuated by the fluidic components and facilitate the creation of circuits that perform a certain function, such as logic-based conditions for gripping an object, or flapping wings based on user input. These paper creatures could serve as an inspiration for users to start creating their own paper designs and operate them pneumatically through the actuators included in the toolkit.

Although we did not evaluate our toolkit from the perspective of any specific educational theory, we here position our approach within two main educational movements: constructivism and constructionism. Within constructivism, learners actively construct knowledge by relating it to knowledge they

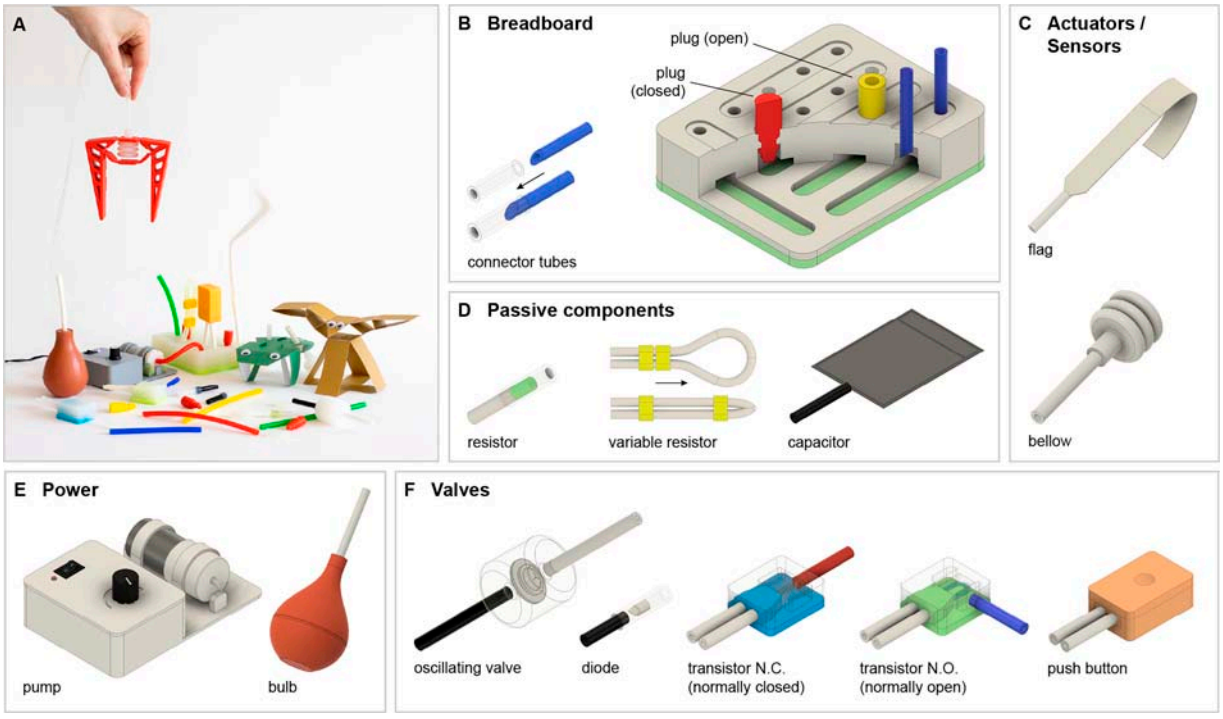


FIG. 1. An overview of the circuit-building components included in the toolkit. At the top center is a cross-section of the fluidic breadboard, including plugs and connector tubes. **(A)** The toolkit in action. **(B)** Breadboard, plugs, and connectors. **(C)** Actuators and sensors. **(D)** Passive components. **(E)** Power components. **(F)** Valves. By combining components from these four categories, different circuits of varying complexity can be built.

already possess,[38] focusing on the creation of mental models. Constructionism shifts this focus to learning by making, of which Papert's programmable Logo Turtle is a prime example.[39] Later developments building on this approach can be seen in MIT's Scratch language[40] and physical computing environments such as Arduino.[22] However, the constructivist and constructionist approaches can require a high level of metacognitive skills from students to monitor and regulate their own learning, and as such guidance is still needed.[41] The soft circuits teaching approach therefore often follows the principle of Rosenshine's scaffolding[42]: The manual contains many worked examples, and every next step in the manual adds only a minimum number of new components, thus guiding the students through the learning process. To encourage the students to develop metacognitive resilience, the manual contains self-check questions without the answers, and there is a strong focus on productive failure.[43] Students are encouraged to debug their circuits directly on the breadboard, thus learning from their mistakes.

The toolkit underwent two major iterations and was tested multiple times with engineering students. User feedback ($N = 8$) on the first iteration was used to develop the second iteration of the toolkit. This second iteration, which is presented here, was evaluated with three user groups ($N = 26$, $N = 27$, and $N = 24$). Based on participants' positive feedback, plans have been made to further develop the toolkit and bring it to market in some form in the future, to allow users to skip the fabrication step and immediately start experimenting with soft fluidic circuitry.

Design Goals

In the initial stage of the design process, we set four goals for the toolkit, derived from the literature as well as our experience with soft robotics: (1) Standardization: two standard connector dimensions were chosen to facilitate easy connections across different components. Component values follow standardized values where possible to speed up prototyping of circuits and facilitate their replicability, as users can easily find components with the same values. To further promote standardization of the toolkit system, its design was modeled after electronics kits. Frequent inspiration was drawn from kits such as Arduino[22] and Boffin.[23] Following the electronics analogy, our toolkit consists of a number of components analogous to those that are commonly found in electronics kits, such as a breadboard, resistors, capacitors, and diodes, as well as more advanced components such as transistors. Some of the included components are useful for building fluidic circuits but do not have a direct counterpart in electronics, such as the oscillating valve; (2) Robustness: components are able to withstand some abuse or misuse expected from inexperienced users; (3) Softness: all components are completely soft, with the exception of the power source, to aid user interaction. Shore hardnesses range from 22 to 85 A; (4) Understandability: fluidic components are intuitive to understand. This includes the implementation of affordances[44] that communicate to users how to use components. This approach prevents users from having to consult a manual to learn how every component works. Instead, the component communicates to the user how it should be used through its shape, material, and color. The use of soft, squishy materials for the components indicates that they can be touched and squeezed. In the push button, for example, this squishiness is combined with selectively placed indents, which together indicate that the push button should be squeezed to work.

Building Fluidic Circuits

The toolkit is accompanied by a manual (Supplementary Data S7) and online platform (www.softcircuitstoolkit.com), which provide information about how components function, as well as tutorials on how to build a variety of circuits, complete with circuit schematics and breadboard layouts. The online platform also offers videos of every circuit to inspire and show the wide range of circuits that users can build. Figure 2 shows four examples of such circuits, with the corresponding videos being available in the Supplementary Videos. A symbol library for the components was created in KiCAD[45] for drawing the fluidic circuits schematically. A visual language was developed for drawing breadboard layouts, which allows those unfamiliar with circuit schematics to be able to copy the example circuits in the manual and on the online platform.

In addition to teaching about fluidic circuits, our toolkit also offers a great opportunity to teach about the analogy between fluidics and electronics, where flow is similar to current and pressure to voltage.[46] For university-level engineering students, who often encounter electronics in their curriculum, this analogy can speed up their understanding of fluidics. With this in mind, the toolkit manual was designed in such a way that knowledge of electronics is not needed, but that any preexisting knowledge can be applied to the exercises in the manual. As an exercise for the reader, we will refer to fluidic components using their electronic analogy throughout the text. Compared to electronic circuits, where feeling electricity would be difficult and unsafe, air circuits permit airflow and pressure being felt by hand, thus facilitating learning.

Building the first circuits

One of the first circuits the user builds when following the toolkit manual is a *hello world* circuit (Fig. 2A). This circuit introduces users to the central idea of the toolkit: air travels through a "fluidic breadboard," connector tubes, and components, thus creating a circuit that carries out a certain function. In the hello world circuit in Figure 2A, the pump pressurizes a single channel (row) of the breadboard via the red silicone tube. As a result of the air pressure building up, the white bellow at the end of the row inflates, indicating a pressure build-up. To prevent the pressure from rising too much and the bellow shooting out of the breadboard, a resistor (tube with a very small inner diameter) venting to atmosphere is added. Atmospheric pressure in the electronics analogy is denoted as "ground." By understanding the working principle behind basic circuits like these, users can start building more elaborate circuits, which gradually introduce them to more complex components.

The *storing energy* circuit in Figure 2B introduces the user to slightly more advanced components, such as the capacitor, flag, diode, push button, and bulb. This circuit shows the capacitor in its energy storage function. By repeatedly squeezing the bulb, the user can inflate the capacitor, thus storing energy in the form of pressure. The trapped air inside the capacitor cannot escape because of the diode (one-way valve) placed between the capacitor and the bulb, and the push button placed after the capacitor. This push button is normally closed

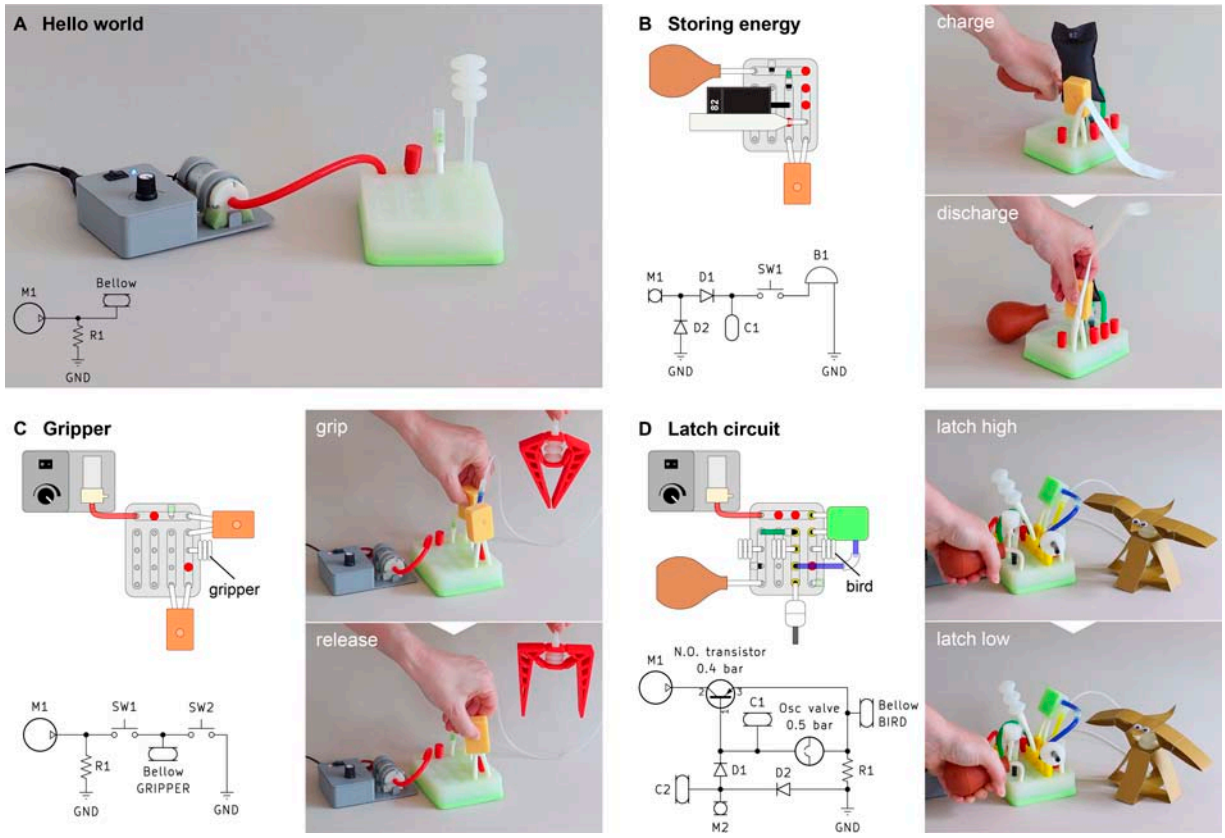


FIG. 2. An overview of various circuits that can be built with the toolkit. **(A)** A basic *hello world* circuit that teaches the workings of the pump, breadboard, connectors, resistor, and bellow. **(B)** A circuit for storing energy in a capacitor and releasing it to power a fluttering flag (flow sensor). No pump is needed. This circuit mainly teaches the storing of energy (pressure) and the functioning of diodes. **(C)** A circuit that teaches how push buttons can be used to actuate a bellow, which in turn opens and closes a compliant gripper. **(D)** A latch circuit that inflates and deflates a bellow that makes the bird's wings flap. The bellow inflating and deflating is controlled by a single press of the bulb (*M2*). The yellow plugs are needed in the breadboard to secure the components as pressures increase to >1 bar.

(N.C.) and will only open when pressed by the user. Upon pressing, the air is able to exit the capacitor and escape through the flag, which will briefly flap from the resulting airflow.

The components

As shown in Figure 1, the components included in the toolkit can be categorized into different categories: breadboard, plugs, and connectors; passive components; actuators and sensors; power components; and valves. These categories will be outlined here, and their components described in more detail.

All toolkit circuits require some type of *connector* to link components. Components can be connected to each other by inserting their tubes into a central fluidic breadboard. This breadboard contains five rows of four interconnected holes each. Similar to breadboards used in electronics, this row configuration allows components to be quickly and easily connected to each other. The red plugs (Fig. 1B) are needed to close any unused row holes to prevent air from escaping. The yellow plugs (Fig. 1B) have a channel running through them and are used to tightly connect male connector tubes (3 mm inner diameter, 6 mm outer diameter) to the breadboard, to create circuits that can withstand pressures up to 1.5 bar. These male connector tubes (blue tubes in Fig. 1B) can also be directly connected to each other with female connector tubes (5 mm inner diameter, 8 mm outer diameter, transparent tubes in Fig. 1B).

The toolkit contains three *passive components*: resistors, variable resistors, and capacitors. To create pressure drops, resistors (Fig. 1D) of different values are included in the toolkit. Here, resistors are very small openings, ranging from an inner diameter of 0.2 to 0.8 mm, embedded in a larger silicone tube. The resistors have one male and one female lead to facilitate daisy chaining with each other or other components. Variable resistors (Fig. 1D) are included to allow users to achieve precise resistance values, as well as provide a simple on/off switch. Resistance is increased by sliding the top yellow slider up, thus kinking and narrowing the opening of a 3×6 mm^2 tube. Capacitors (Fig. 1D) are included in the form of inflatable fabric pouches. These capacitors can be used to store energy (pressure) and can be used as filters to dampen pressure fluctuations or used as delays to increase charging time in part of a circuit. For the capacitor volumes, an E12 series of preferred numbers[1] was followed for volume in milliliters, ranging from 27 to 100 mL. Smaller

[1]The E series of preferred number is commonly used in electronics. The E12 series contains the following 12 values per decade: 10, 12, 15, 18, 21, 27, 33, 39, 47, 56, 68, 82.[47]

values were not included as in practice they were too small to be used in the circuits.[47]

To indicate airflow and pressure, the flag and bellow (Fig. 1C) can function as *actuators* or *sensors*. These components can be used in circuits to indicate that the pump and circuit are working and that air is flowing. In Figure 2B, after sufficient pressure is built up in the capacitor, this pressure can be released by pressing a push button. The flag then briefly flaps, which gives a clear visual indication of the air escaping the capacitor. In more advanced uses, the flag can act as a simple oscillator that always vents to atmosphere. In the *hello world* circuit, the bellow can function as a pressure indicator when the resistor is manually closed by placing a finger on top of it. As the resistor is closed/opened, the bellow inflates/deflates. This straightforward interaction provides a powerful visual to learners about the relation between resistance and pressure build-up. The bellow can also be used as an actuator that activates other components, such as the bird, frog, and gripper shown in Figure 1A.

The *hello world* and *storing energy* circuits demonstrate the two options to *power* the circuits (Fig. 1E): power by the pump and manual power by the inflation bulb. The pump features an on/off switch and flow adjustment knob for easy operation. The magnitude of the flow output can easily be visualized by connecting the pump to a flag circuit, where smaller airflow causes the flag to flap slowly, and greater airflow causes it to flap more quickly. The bulb can also be used to transfer a specific amount of air. In such a circuit, the bulb can inflate/deflate a bellow upon squeeze/release of the bulb or activate/deactivate a transistor (Fig. 2D).

For the creation of more advanced circuits, a variety of *valves* is included in the toolkit, such as push buttons, diodes, an N.C. transistor, a normally open (N.O.) transistor, and an oscillating valve[14] (Fig. 1F). The push button is introduced early in the manual as it offers a simple way of activating components, such as the flag in Figure 2B. By combining two push buttons, more advanced circuits become available to the user, such as opening and closing the gripper in Figure 2C. Similarly, in its most basic implementation, the transistor can function as a push button when the bulb is connected to the transistor gate. In this configuration, the N.C. transistor opens when the bulb is squeezed, and the N.O. transistor closes when the bulb is squeezed. However, we can also combine the transistors with other components to create circuits that derive their functionality from different activation pressures. In Figure 2D, we show that by combining an N.O. transistor that has a lower gate threshold pressure with an oscillating valve that has a higher opening threshold pressure, we can create a *latch circuit* that inflates and deflates a bellow through interaction with a single volume, similar to how a latch circuit functions in electronics. With a single bulb, the user can thus position the bird's wings in an upward or downward position.

Many of the components in the toolkit rely on existing designs in the field, such as the oscillating valve, pouch capacitors, and small tubes that act as resistors. However, new operating mechanisms were designed for the push button, transistors, and variable resistor, which rely on the kinking and unkinking of a silicone tube. Previous research has shown this kinking behavior to be promising for use in soft robotics projects.[48] Figure 3 shows the characterization of the N.C. transistor, N.O. transistor, and push button. Per component, 11

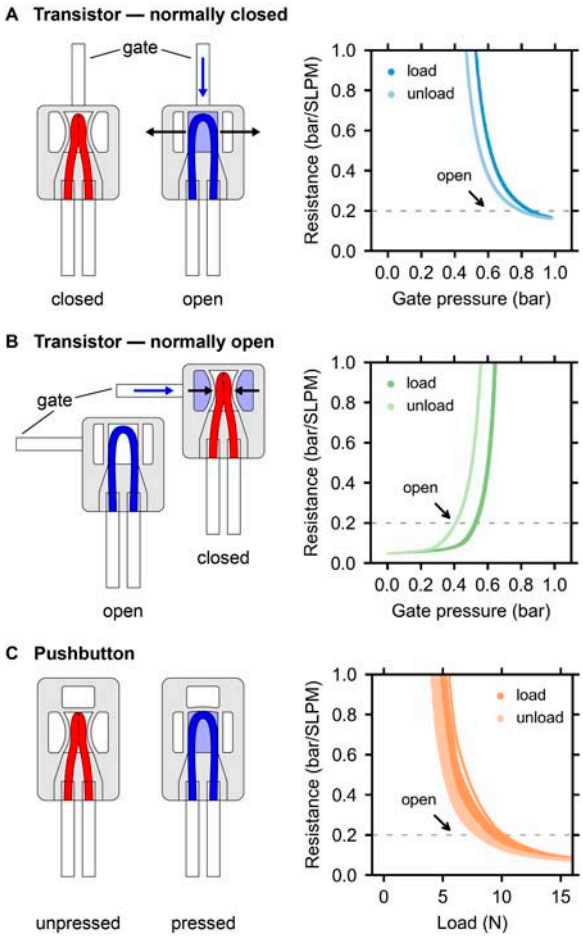


FIG. 3. Overview of the transistor and push button components. **(A)** N.C. transistor. *Left*: Inner working mechanism. *Right*: Resistance drop in the transistor as gate pressure increases. The N.C. transistor opens at a gate pressure of 0.85 bar when being loaded and closes at a gate pressure of 0.80 bar when being unloaded. **(B)** N.O. transistor. *Left*: Inner working mechanism. *Right*: Resistance increase in the transistor as the gate pressure increases. The transistor closes at a gate pressure of 0.53 bar when being loaded and opens at a gate pressure of 0.41 bar when being unloaded. **(C)** Push button. *Left*: Inner working mechanism. *Right*: Resistance drop as force is applied to the push button (squeezing). N.C., normally closed; N.O., normally open.

measurements were done, of which the first measurement was discarded. We report on the measurement procedure in Supplementary Data S1. To create these components, we exploit the kinking of a 1.5×3 mm^2 silicone tube to create an N.C. transistor, an N.O. transistor, and a push button. Here we leverage the relatively small force needed to kink a tube, thus enabling gate pressures of roughly 0.40–0.85 bar to open and close tubes, which are pressurized at 1.0 bar. As pressure is applied to the gate port, the internal 1.5×3 mm^2 tube unkinks because it is glued to the inner walls, which expand as the inner volume expands. Similarly, the push button opens at forces of 5–10 N, which can be applied manually. The indicated opening resistance of 0.2 bar/SLPM is based on our observations of what constitutes a low enough resistance for a component to be considered "open." However, this value was chosen somewhat arbitrarily and could depend

on the user interacting with the button. To give some intuition, at a pressure difference of 0.2 bar, a 100 mL capacitor would take 4.7 s to empty to 2% of its initial value through an open button with a resistance of 0.2 bar/SLPM. We provide the calculation for this deflation in Supplementary Data S1. Across 10 measurement cycles for the individual transistors, resistances varied roughly 0.01 bar/SLPM for the corresponding gate pressures. Resistances between cycles showed an average standard deviation of 0.010 for the N.O. valve and 0.004 for the N.C. valve, which indicates that the transistors are reliable in their functioning. During testing of the 3 N.O. and 3 N.C. transistors, we did not observe any leakages or failure modes. However, some variability (0.12–0.33 bar) between the opening gate pressures of different N.O. and N.C. transistors was observed. We report on this variability in Supplementary Data S1. During the user tests, differences between opening pressures were not remarked upon by the participants. From our observations, this manufacturing variability between transistors poses no problem for learning and applying the theory, and using the components included in the toolkit.

More complex circuitry

In addition to the above-mentioned interactive circuits, we also demonstrate an oscillating circuit that showcases the implementation possibilities of the toolkit. By actuating the gripper, bird, or frog model, users are invited to create their own devices and "robots," which can be actuated by the bellows and controlled through the pneumatic circuits. The circuit shown in Figure 4 features a paper bird flapping its wings as a result of the oscillating valve opening and closing. The flapping frequency can be set by changing the value of a variable resistor that is placed downstream from the valve, which effectively decreases (increases) the pressure over the valve, thus increasing (decreasing) the frequency at which the valve and the bird wings oscillate. We report on the measurement procedure for this circuit in Supplementary Data S1. For these more complex circuits, the electronics analogy becomes less helpful, and as a consequence, it becomes more important to implement the understanding of fluidics developed through building the earlier, more basic, circuits. The electronics analogy is helpful for reaching this level of understanding, together with the hands-on experience users gain from building circuits. Additionally, when building these more complex circuits, it becomes apparent that certain outcomes that are difficult to achieve in electronics circuits are easy to build in fluidics circuits and vice versa.

The circuits described in this section allow users to become familiar with a range of fluidic components and the circuits these components can build. By including a gripper and paper animals, the focus shifts from circuit building to including the embedding of circuits in robotics projects. By introducing a compliant gripper, users further become familiar with the concept of embodied intelligence, as the compliance of the gripper enables the grasping of a variety of objects without any sophisticated control circuits, instead relying on simpler pneumatic circuits.

Evaluation

The toolkit underwent two major iterations, which were both evaluated with engineering students over four user testing rounds. Feedback on the first iteration was used to develop the second iteration of the toolkit, which is presented in this article. User testing followed protocols (Supplementary Data S2) to ensure uniform conditions within user testing rounds. As participants signed up voluntarily for the user tests, self-selection bias in the participant groups could have occurred, which could have skewed the results presented here in a more favorable direction. To keep user test length manageable, the first two

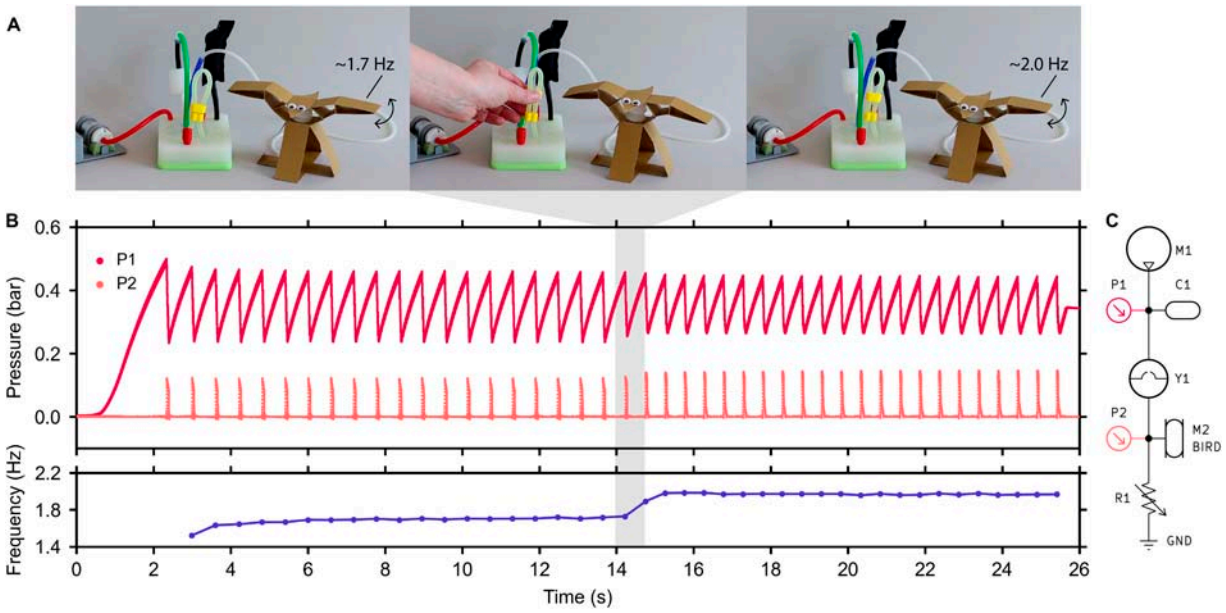


FIG. 4. Oscillating circuit that responds to user input (increasing the resistance) to change the frequency at which the bird wings flap. **(A)** The circuit built on the breadboard. First the bird flaps at a frequency of ∼1.7 Hz. A user interaction occurs at $t = 14$ s, which increases the flapping frequency to ∼2.0 Hz. **(B)** The pressure and frequency measured in the circuit over time. At $t = 0$ s, the pump is turned on, and the valve reaches a steady frequency after a few seconds. At $t = 14$ s, the resistance (*R1*) downstream to the valve is increased, which causes the frequency of the oscillation to increase. At $t = 25.5$ s, the pump is turned off. **(C)** Circuit schematic of the setup.

Table 1. Test Components and Evaluation Methodology

Test	*Component (version)*	*Participant background*	*Evaluation method*
1	Breadboard Plugs Connector tubes Pump Bellow N.O. transistor N.C. transistor (v1) Push button (v1) Resistor (v1) Flag (v1)	Industrial Design students ($N = 8$)	Observation, knowledge-check questions, self-efficacy questionnaire
2	Breadboard Plugs Connector tubes Pump Diode Capacitor Push button (v2) Resistor (v2) Flag (v2)	Industrial Design and Mechanical Engineering students ($N = 26$)	Observation, quiz questions, UEQ
3	All components	Athens students 2024 ($N = 27$)	UEQ
4	All components	Athens students 2025 ($N = 24$)	UEQ

N.C., normally closed; N.O., normally open; UEQ, User Experience Questionnaire.

user testing rounds did not evaluate all components included in the toolkit. For an overview of which components where evaluated at each test phase, see Table 1.

User test setup

In the first user test, the first iteration of the toolkit was formatively evaluated by eight participants, individually, all Industrial Design (ID) students (bachelor and master level) at a technical university in Northwest Europe. Participants' circuit-building self-efficacy (following[49]) was assessed before and after the test. Participants built a number of circuits with the aid of a manual (Supplementary Data S9) adapted specifically to the user test. Their understanding of the circuit concepts taught in the manual was checked via knowledge-check questions[50] included in the manual. The questionnaire questions and results of this user test can be found in Supplementary Data S3.

The shortcomings identified in the first user test were addressed in the second iteration of the toolkit, which was evaluated in the second user test with 26 participants in groups of two to three, or occasionally individually, all Mechanical Engineering (ME) or ID students (bachelor and master level) studying at a technical university in Northwest Europe. The user test evaluated intuitiveness, user experience, facilitation of problem-solving behaviors, and understanding of circuit building theory and principles such as series and parallel circuits. To evaluate these aspects, participants completed three tasks: (1) build a number of circuits with the aid of a manual (Supplementary Data S8) adapted specifically to the user test; (2) fill in a validated User Experience Questionnaire (UEQ)[51] to measure user experience across six different scales (described in more detail in Supplementary Data S4); and (3) adapt three circuits to perform a certain function by including a given component (Supplementary Data S5).

In user tests 3 and 4, both student workshops, the entire toolkit (second iteration) was tested with 27 and 24 participants, respectively, during a soft robotics course taught as part of the Athens university exchange program. Participants were all students at European universities enrolled in a technical degree (bachelor and master level). During this workshop, participants worked through the final, full version of toolkit manual (Supplementary Data S7) in groups in 1 h and subsequently filled in the UEQ individually. They spent the remaining 1.5 h of the workshop building their own circuits and completing challenges (Supplementary Data S6). Throughout the workshop, researchers were present to guide students. The main focus of the workshop was to validate user experience through the UEQ. Students were not closely observed for specific behaviors, nor were their answers to the challenges evaluated.

User testing results

In the first user test, all participants were able to finish the manual steps within 45 min without any help from the researcher. The self-efficacy test showed a significant ($p < 0.05$) improvement in perceived self-efficacy for seven out of the nine questions (Supplementary Table S2), which suggests that use of the toolkit increases (perceived) circuit-building efficacy. The knowledge-check questions in the manual were mostly answered correctly by the participants (6 out of 10 questions answered correctly by all participants) (Supplementary Table S3). Researcher observation revealed that participants showed some difficulty in using the push button, N.C. transistor, and resistor. Taken together, the findings from user test 1 indicated that the toolkit showed promise for soft circuit building, but more development needed to be done on the components included in the kit, especially because certain fundamental circuit-building components (the diode and capacitor) were not yet included in the toolkit.

In the second user test, participants were able to learn how to use the components from the manual without researcher help and finished the test within the allocated 45 min. In three instances, a comment from the researcher was needed because participants were not using a plug or tube correctly, which was preventing them from completing a certain circuit. These cases were minor, however. No researcher intervention was necessary to explain how to use any of the other components.

The quiz results (Supplementary Table S4) from user test 2 mirror the observational findings but should be evaluated carefully. As most participants worked in groups, they were able to influence each other in their individual answers to the questions. Nevertheless, these results give an indication of the level of understanding of participants. All participants answered question 1 correctly, about series versus parallel circuits, and only one participant misplaced the capacitor in question 3. Question 2, which required a grounded diode to be inserted into the circuit, caused the most difficulty, with 9 out of 26 participants drawing an incorrect answer (1 ME student, 8 ID students). These answers show that participants generally understood the functioning of the components, including the diode, but some struggled with the concept of ground (the atmospheric pressure around us). Because of question 2, ME students far outperformed ID students on the quiz. It is difficult to say with any certainty what caused this discrepancy, as not all students took the same courses in their studies. Possibly, ME students have a greater knowledge of electronics and are able to apply this background knowledge to pneumatic circuit functioning. To further clarify the concept of atmospheric pressure and ground, a short textual and visual explanation of the concept was included in the final version of the toolkit manual on page 5.

Figure 5A shows the results of the UEQ for user tests 2, 3, and 4 (error bars represent 95% confidence intervals). The toolkit scored well on all scales, with "Attractiveness" scoring the highest among all groups, and very well for the Athens groups in particular (+2.5 mean score, where it is unlikely to find scores exceeding +2.0[52]). These questionnaire results support the qualitative results, with participants generally being positive about the toolkit as a whole, but also indicating that they experienced some difficulty with some aspects of the toolkit, such as inserting plugs far enough or understanding the concept of ground, which could explain why Efficiency and Dependability scored slightly lower among ME and ID students.

The Kruskal–Wallis test was conducted to examine the difference in UEQ scores between user tests 2, 3, and 4. The results indicate a significant difference between the three groups, $H = 9.17$, $df = 2$, $p = 0.010$. The Mann–Whitney U test showed that the Athens 2024 students rated the toolkit significantly higher than the ID and ME students, $z = -2.64$, $p = 0.004$. Similarly, the Athens 2025 students also rated the toolkit significantly higher than the ID and ME students, $z = -2.32$, $p = 0.015$. No significant difference between ME and ID students was found, $U = 21.0$, $p = 0.688$, or between Athens 2024 and 2025 students, $z = -0.40$, $p = 0.699$. These findings suggest that the complete toolkit provides an overall more positive user experience compared to the toolkit that does not include all components. However, care needs to be taken with this interpretation, as participant backgrounds and test settings differed between test 2 compared to tests 3 and 4.

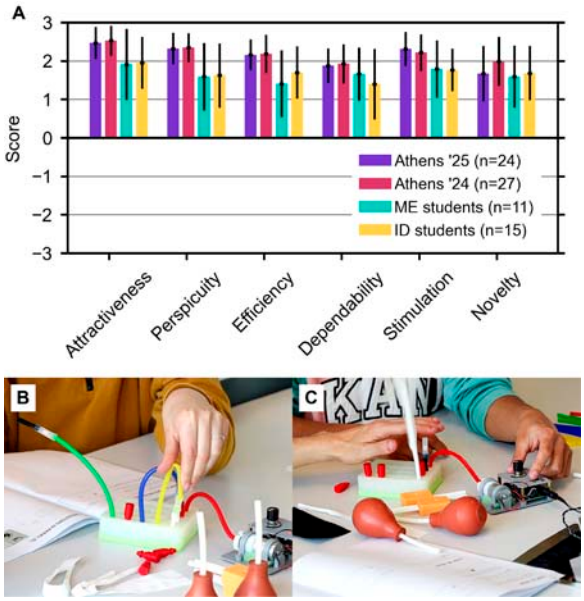


FIG. 5. Results of user tests 2, 3, and 4. **(A)** Results of the UEQ administered to the user testing participants. The toolkit was largely evaluated very positively, with *Attractiveness* scoring the highest for all test groups, while *Dependability* generally scored relatively lower for the groups. **(B)** ID student directly interacting with the built circuit. The student is closing one tube to observe the difference in airflow between a single resistor or two resistors in parallel. **(C)** ME student feeling by hand if air is escaping from the diode, to establish that the diode is a one-way valve, and to determine the directionality of flow in the diode. ID, Industrial Design; ME, Mechanical Engineering; UEQ, User Experience Questionnaire.

Overall, problem-solving behaviors were commonly observed during user tests 1 and 2. Participants frequently touched components to assess how they functioned (as seen in Fig. 5B, C). When answering the challenge questions, participants often tested their assumptions and ideas by building the circuits and then observing how they behaved, and if necessary adapting their answers to the questions. One group (P26–28), for example, extensively used the breadboard to try out different answers to challenge questions when they thought they could improve their answer. This shows that the toolkit can offer direct, tangible opportunities for testing out ideas and seeing how they work.

Participants often indicated how the toolkit helped form their understanding, especially through the analogy between fluidics and electronics: "Nice that it looks like a breadboard, [. . .] then you also know when you want to do electronics, how that is connected to each other," (P18) and "The fact that this toolkit helps you to associate [. . .] the pneumatics and electronics is [. . .] a big step for people to understand electronics." (P5) One participant explicitly connected this analogy to the lowering of barriers: "The barrier is just a little lower [compared to electronics], because it's slightly bigger objects, more tangible." (P17) Despite some participants showing problems understanding the concept of "ground," there were also some participants who understood the

analogy on a deeper level, such as P8: "Ground is escape of the air. Without ground there's no circuit." Two participants explicitly appreciated the usability robustness of the components: "You can play safely without blowing anything up," (P10) and "This is hands-on experimenting and testing [. . .] without being afraid that something will break." (P23)

Some participants specifically mentioned the strength of visualization of the toolkit and how it improved their understanding: "[In electronics courses] we always had to measure voltage and current, but numbers don't say that much. [. . .] I can see [. . .] where the air is going. Capacitor inflates, you can see that." (P8) "I'm a noob [novice], especially when I can't see the electricity. Here you can see it." (P16) "It's really nice. I wish I had this when I was doing electronics. Now I see after 7 years. You see how [. . .] everything [. . .] works. Oh, it's a capacitor [because] it fills up." (P4) Finally, almost all participants expressed their enjoyment in building the circuits and interacting with the toolkit: "It's a nice puzzle way to learn how all of this works. So that's really fun," (P23) and "You learn really easily with this." (P28)

After user testing was completed, the toolkit was demonstrated at a Maker Faire (visited mainly by primary school children) and a 9-day international design event open to the general public (visited by adults and children of all ages), further demonstrating the usability robustness of the components included in the toolkit, and its potential for teaching circuit-building through pneumatics to a broader audience. Moreover, the circuits described in the previous section demonstrate a range of what can be built with the components included in a single toolkit. This limits users to the use of a single N.O. transistor, N.C. transistor, and oscillating valve. At the Maker Faire and design event where multiple toolkits were available to visitors, we observed users experimenting with circuits that involved multiple transistors and oscillating valves. Excluding these public events, the toolkit in its current form has been tested with 85 participants over 3 years. During these tests, some capacitors failed due to fabrication errors and the push buttons were all replaced once due to internal failures. The overall lack of failures in the majority of the components over an extended period of time highlights the high mechanical robustness of the toolkit. Nevertheless, further durability testing is needed to make any quantitative claims about this robustness.

Conclusions

This article presents the design, fabrication, and evaluation of the Soft Circuits Toolkit, aimed at teaching novices and more advanced users about completely soft, fluidic circuit design. The toolkit mainly serves as a teaching tool, but it also enables prototyping of soft robotics projects and provides inspiration for newcomers and those with more advanced circuit-building skills. By offering a ready-made kit, we eliminate the fabrication step from soft robotics prototyping, thus enabling students (and other interested learners) to directly experiment with fluidic logic circuits. This focus on fluidic logic also allows students to start developing an understanding of physical control, as our toolkit does not make use of a central control unit, instead embedding the logic in the different components themselves. The results from our user tests indicate that the toolkit is engaging, shows good learnability, and is suitable for teaching understanding and troubleshooting of pneumatic circuits. We expect that this toolkit could be a great asset for technical universities looking for effective ways to inspire and teach students about (fluidic) circuit building and soft robotics. For children, a simplified version of the toolkit might be suitable to teach circuit-building skills. However, additional user studies with the target group should be performed to evaluate the best format for the toolkit simplification. It is our goal to bring the Soft Circuits Toolkit to market in some form to continue this research avenue.

To make this toolkit easily available to the soft robotics community, we have shared all fabrication files, such as molds, print files, and print settings, as well as detailed fabrication videos for each component on our website, www.softcircuitstoolkit.com. We have made data underlying this work available in an open-access repository (https://doi.org/10.4121/4345de36-710c-496d-b6f1-457416be9e32). We believe that our approach lowers the barrier to entry to soft robotics prototyping and education, and we expect that it is essential for the continued lowering of this barrier that such toolkits will be mass-produced in the future.

Acknowledgments

The authors thank Benjamin Gorissen and Franco Nicolas Piñan Basualdo from KU Leuven for their help in user testing the toolkit. The authors are grateful to all the members of the Soft Robotic Matter group at AMOLF for the invaluable discussions.

Authors' Contributions

C.M.v.R.: Conceptualization (lead), investigation (lead), methodology (equal), visualization (lead), writing—original draft (lead), and writing—review and editing (equal). S.Z.: Conceptualization (supporting), methodology (equal), supervision (supporting), and writing—review and editing (equal). F.L.M.D.: Supervision (supporting) and writing—review and editing (supporting). A.v.O.: Supervision (supporting) and writing—review and editing (equal). J.T.B.O.: Conceptualization (supporting), methodology (equal), supervision (lead), and writing—review and editing (equal).

Author Disclosure Statement

The authors declare that they have no competing interests.

Funding Information

This work was supported by European Research Council Starting Grants (grant agreement ID: 948132). This work is part of the Dutch Research Council (NWO) and was performed at Eindhoven University of Technology and the research institute AMOLF.

Supplementary Material

Supplementary Data
Supplementary Video

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Address correspondence to:
Johannes T.B. Overvelde
Autonomous Matter Department, AMOLF
Science Park 104
Amsterdam 1098 XG
The Netherlands

E-mail: overvelde@amolf.nl