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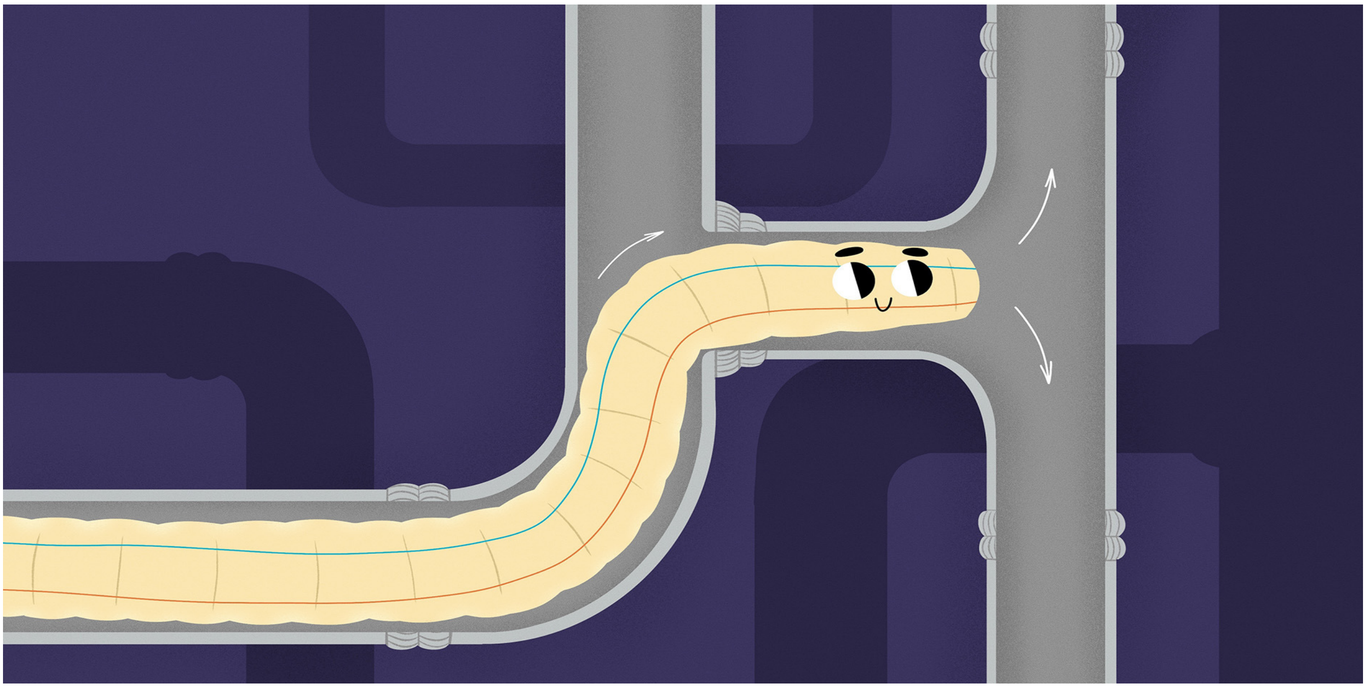

WHY ROBOTS SHOULD GROW LIKE VINES

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YOUNG REVIEWERS:

ADITYA
AGE: 14

ARUN
AGE: 11

STEPHANIE
AGE: 13

When a vine grows up the side of a building or through a crack in the sidewalk, it lengthens from its tip. This allows it to easily grow around obstacles and squeeze through small holes. Its body forms a path back to its roots, where it draws water and nutrients from the soil to continue growing. This idea has inspired growing "vine robots", soft, air-powered robots that lengthen from the tip by pushing out material stored inside their bodies. Acting like robotic plants, vine robots can move easily through cluttered areas like vines can, and they can also do robotic tasks, like carrying cameras and other tools. This combination can help doctors reach inside the human body, archeologists see inside ancient ruins, inspectors see inside pipes, and more. It is exciting to think about how robots that grow like vines will help people in the future.

ROBOT

A machine that can sense, make decisions, and act in the physical world.

HOW DO PLANTS GROW?

When designing a new type of **robot**, we might take inspiration from how nature does things. Growing is a very interesting behavior that plants and animals both do, but in different ways. People grow as they become adults and then stop growing, but plants change their growth to respond to what is happening around them [1]. We call this **plant plasticity**, with plasticity meaning the ability to be molded or changed, like plastic. Since plants cannot get up and walk to find food, they instead grow and change their shapes to find more water, light, and space (Figures 1A, B). But how do plants grow without having a plan ahead of time? Plants grow by adding new material to the end of a branch or root. This means they can decide where to move next whenever they grow. Click here to watch a video of plant roots growing and changing direction.

PLANT PLASTICITY

The way that plants can respond to their environments by changing how they grow.

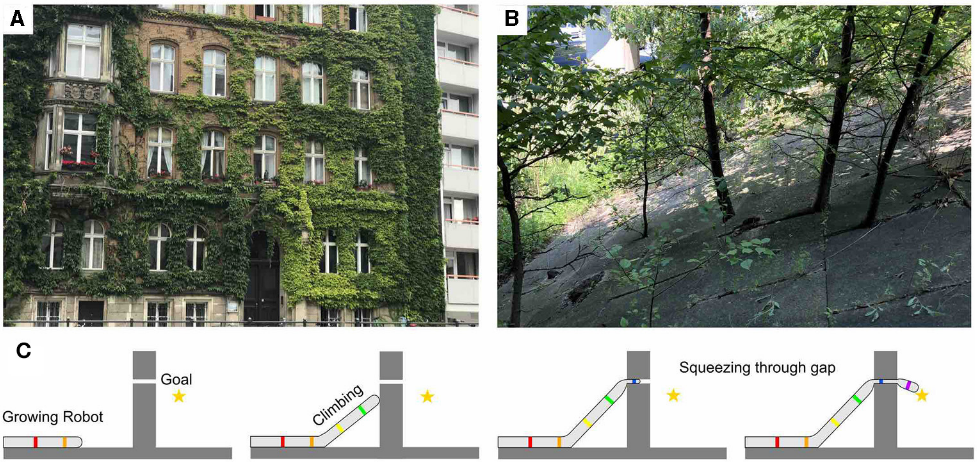

Figure 1

Figure 1

Benefits of growth for plants and robots. **(A)** Vines can climb structures, like buildings, to get more exposure to the sun. **(B)** Trees can grow through concrete by squeezing through cracks. **(C)** Growing robots use their growth to climb up and over obstacles and squeeze through gaps to reach their goals. The colored bands show how the robot continues growing from the tip, and only the tip, to achieve this [image credits: **(A)** TEAVBE from Reddit and **(B)** Famartin from Wikimedia Commons].

BENEFITS OF GROWTH FOR PLANTS AND ROBOTS

The ability to grow from their tips is incredibly important to plants, since it lets them get around or through obstacles that would otherwise stop them. Plants grow their roots into soil to reach for nutrients, and they grow taller to catch more sun. The entire plant is connected, moving nutrients and energy between the roots and leaves. Growth also means that plants can move through places that are hard to get to, like vines climbing the sides of buildings (Figure 1A), and trees growing through cracks in concrete (Figure 1B).

Researchers want to make robots that can do things in the world the way plants and animals do. Taking inspiration from plants, engineers have given robots the ability to grow so they can get around obstacles in their paths, letting them climb over or squeeze through areas to keep moving. Figure 1C shows how a growing robot works. By adding material to its tip, a growing robot can get longer, climb up a wall, and squeeze through a small gap to reach a goal.

CHALLENGES OF ROBOTIC GROWTH

While growing like a plant can help robots do new things, it is also challenging. One challenge is figuring out how to add new material to the tip of the robot. Some growing robots carry their new material inside them. The challenge is how to move it through the robot and how to add it to the correct location. Other growing robots just carry the building blocks to make new solid material. The challenge is then how to assemble those building blocks at the tip. One example of this second robot type has liquid material flowing inside its body that transforms to solid when exposed to light [2]. Click here to watch a video of this robot navigating a maze.

Another challenge is how to make a growing robot steer in the correct direction. The robot's **actuators** could steer just its tip, or they could steer its whole body if the robot needs to be able to wrap around something. Since the robot can be very long, researchers need to be clever with how they attach actuators to the robot's body and where they attach them to make sure they can steer the robot in a useful way.

ACTUATOR

A part of a robot that makes it move and/or apply forces on its environment.

A final challenge for robots growing like plants is how they can sense both themselves and the world around them. A robot may want to see where it is going, so it needs a **sensor** at its tip. However, when new material is added, the sensor will need to move into this new piece to stay at the tip. Sensors can also be along the length of the robot, but as with actuators, we must consider where the sensors are needed. This requires researchers to come up with smart designs that can move sensors to the right places.

SENSOR

A part of a robot that detects information about the robot or its environment.

VINE ROBOTS—BASIC PRINCIPLES

One exciting way of making a robot grow like a plant is called a **vine robot** [3]. Click here to watch a video of a vine robot growing and doing tasks.

VINE ROBOT

A robot that "grows" from its tip by using fluid pressure to turn its flexible body material inside-out.

A vine robot's body is a hollow tube of material that is flexible but not very stretchy. Often, the body is made of a thin plastic bag or waterproof fabric like that used in camping tents. The material can rip, but that is usually not a problem, like in this video where the robot grows through nails. The robot body tube is folded inside of itself, so that it becomes two layers: an outer layer and an inner layer. The outer layer is the robot that has already grown, and the inner layer is the new material to add to the tip. The vine robot inflates the outer layer using air or another fluid like water. When the pressure of the fluid increases, the inner layer of the material is pushed out of the robot's tip and becomes part of the outer layer, making the tube "grow" from the tip (Figure 2A). Vine robots can grow to enormous lengths by storing the tube material compactly inside a base.

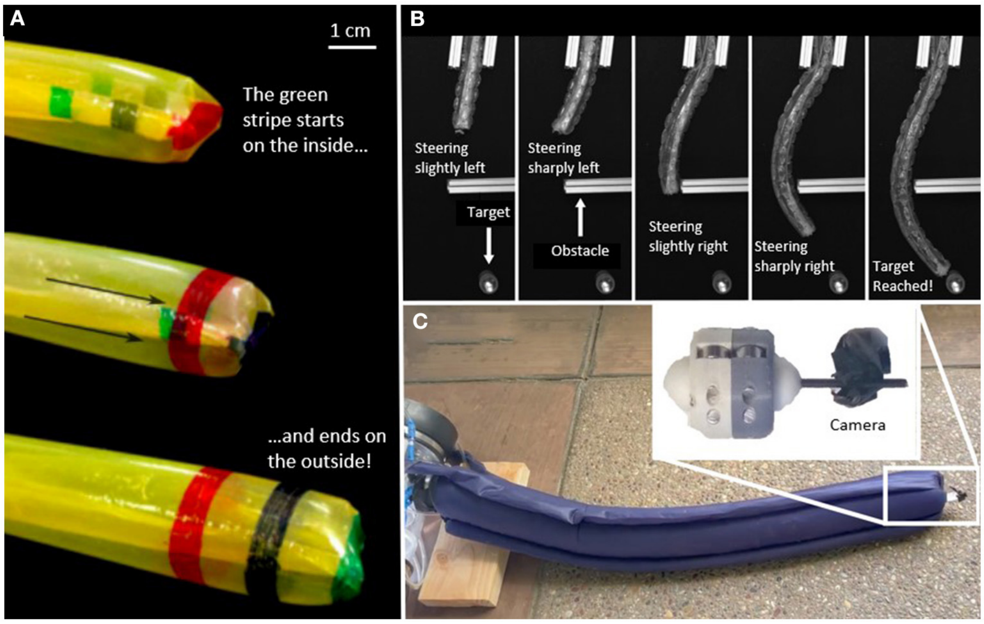

Figure 2

Figure 2

Principles of vine robot operation. **(A)** Growing: A vine robot extends from the tip, using internal air pressure to turn its body material inside-out. **(B)** Steering: A vine robot uses pneumatic artificial muscles to steer its body to go around an obstacle and reach a target. **(C)** Carrying: A vine robot carries a camera at its tip using an interlocking ring and ball mechanism [Image credits: **(A)** Modified from Hawkes et al. [3]. Reprinted with permission from AAAS. **(B)** Modified from Greer et al. [4]. The publisher for this copyrighted material is Mary Ann Liebert, Inc. publishers. **(C)** ©2021 IEEE. Reprinted, with permission, from Heap et al. [5]].

PNEUMATIC ARTIFICIAL MUSCLE

A type of actuator that shortens or lengthens when inflated with air.

When a vine robot needs to choose where to move, it can steer its body by curving it. One way to do this uses **pneumatic artificial muscles**, actuators that act like muscles but use air to shorten or lengthen when inflated. When a pneumatic artificial muscle attached to the robot body is shortened, the robot body curves toward the shortening muscle. This is like your muscles: when your body shortens the muscles on the inside of your palm, your fingers bend toward your palm. With three pneumatic artificial muscles around the robot's body and along its entire length [4], the robot can steer itself in any direction. As the robot body grows, these muscles grow along with the robot, so they can always steer the tip (Figure 2B). Click here to watch a video of a vine robot steering with pneumatic artificial muscles.

For a vine robot to see where it is going, it is helpful to place a camera at its tip. One way to do this uses two pieces that fit together: one piece outside the robot that holds the camera, and another piece inside the robot that keeps the camera from falling off [5]. This allows the camera to move with the robot tip, while the robot body material turns inside-out underneath it (Figure 2C). Click here to watch a video of a vine robot carrying a camera this way. To send the images recorded by the camera back to a computer at the robot base, a wire can run along the body of the robot, so the information can be carried along the length like plants carry nutrients.

USES FOR VINE ROBOTS

So, what does all this mean? What can vine robots be used for? There are several uses of vine robots already in practice and many others that may be soon. Figure 3 shows examples of vine robots in action.

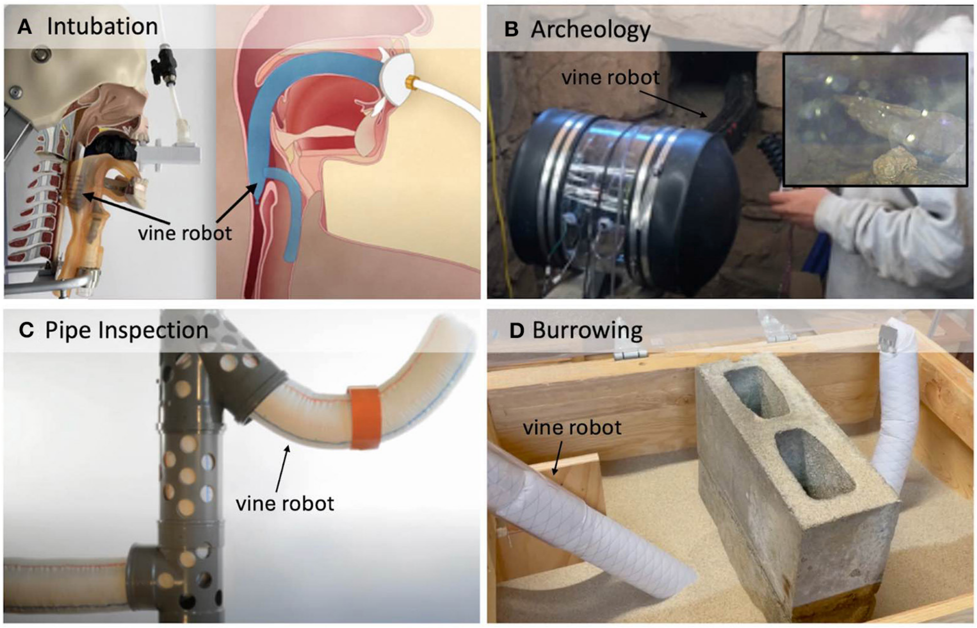

Figure 3

Figure 3

Vine robot uses. **(A)** Intubation: A vine robot is used to keep a person's airway open. **(B)** Archeology: A vine robot explores tunnels with a camera at an archeological site; the view from the camera is shown in the top right corner. **(C)** Pipe inspection: A vine robot navigates through a pipe and through an orange ring a short distance away. **(D)** Burrowing: A vine robot burrows through sand and under a cinder block before emerging on the opposite side [image credits: **(A)** Figure adapted from here. **(B)** ©2020 IEEE. Reprinted, with permission, from Coad et al. [6]. **(C)** Figure adapted from here. **(D)** Figure adapted from here].

Vine robots have a lot of potential in the medical field. Figure 3A shows a vine robot being used to keep a person's airway open so the person can breathe, even if their airway is damaged or they are unconscious. Using the benefits of growing like plants, vine robots can squeeze through this gap and take the shape of the patient's airway, to safely and easily open it. Click here to watch a video of this vine robot in action.

Another use for vine robots is exploring small or dangerous spaces where people cannot go. Figure 3B shows a vine robot exploring an archeological site. Parts of the ruins included a tunnel that was inaccessible to humans or other robots. The vine robot could navigate through the tight spaces and up the walls while carrying a camera to show the inside [6]. Click here to watch a video of the archeology vine robot.

Pipe inspection is also a good use for vine robots, as shown in Figure 3C. Because vine robots can squeeze into small spaces and make tight turns, they can transport sensors or other objects to a goal location inside a pipe network. Click here to watch a video of the pipe inspection vine robot.

Vine robots can even act like a plant's roots. Figure 3D shows a vine robot burrowing into and through sand, by spraying pressurized air to make space for the robot to grow [7]. Click here to watch a video of the burrowing vine robot.

All these uses come with challenges, like figuring out how small or large we can make the robot, or what materials can be used. But with more research, even more uses for vine robots may be possible soon. They may carry water to help firefighters or navigate through rubble to find victims of natural disasters. Maybe they will grow around people to help them move, or travel into space to explore other planets! Imagine all the exciting possibilities when robots grow like plants!

ACKNOWLEDGMENTS

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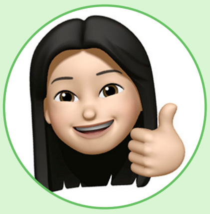
CONFLICT OF INTEREST: LB has a patent on the combination of growth and steering of vine robots. MC has a patent on a method of adding distributed sensors on a vine robot. LB and MC have a pending patent on a device for retracting vine robots.
The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ADITYA, AGE: 14
Hi, I am Aditya. My interests are reading, STEM, and the flute. I enjoy reading (mostly fantasy and literary non-fiction) because of its aspect of immersion, placing my full attention on the world and story sculpted by the author. I enjoy the flute for a similar reason, focusing on a calming and stimulating activity. As for STEM, I believe that the pursuit of knowledge is an admirable and fulfilling goal, so I feel some amount of satisfaction when I learn something new.

ARUN, AGE: 11
Hi, I am Arun. I like Math and my favorite subject is history. I like history because it helps me imagine everything in the past that is important. I want to be a zoologist when I grow up because I like animals. I want to learn about how animals can change our way of life as we know it today. Also, I want to learn how taking away one animal, changing an animal, or adding a new animal affects the ecosystem and food chain. I play soccer and badminton. I love playing video games and watching movies.



STEPHANIE, AGE: 13
My name is Stephanie and I am 13 years old. I am a 7th grader in middle school and my hobbies include singing, playing tennis, and playing the clarinet. My favorite subject in school is ELA and I enjoy reading and writing mystery and dystopian stories. I have performed for the UniverSoul Circus before and I have been a reviewer for some scientific articles in this journal.

AUTHORS

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Ciera McFarland is a Ph. D. student in aerospace and mechanical engineering at the University of Notre Dame. Before Notre Dame, she earned her B. S. in aerospace engineering from Pennsylvania State University in 2021. Her research focuses on vine robot navigation, specifically modeling the shapes vine robots can form into without

collapsing and how this model can inform the ways in which these robots move through an environment. Beyond work, she enjoys reading and crocheting.

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Francesco Fuentes is a Ph. D. student in mechanical engineering at Purdue University. He received his M. S. in mechanical engineering from Purdue in 2022 and his B. S. in mechanical engineering from Marquette University in 2020. His research focuses on soft robot simulation and actuation, as well as unique ways of pushing the limits in current soft robotics understanding and development. Outside of classes, Francesco enjoys rock climbing and playing board games.

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Allison Fick is a Ph. D. student in aerospace and mechanical engineering at the University of Notre Dame. She was also an undergraduate at Notre Dame, earning her B. S. in mechanical engineering there in Spring 2023. Her work is focused on vine robots and their uses. Outside of her research, Allison enjoys rowing, running, and playing board games.

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Laura Blumenschein is an assistant professor of mechanical engineering at Purdue University. She received her Ph. D. in mechanical engineering from Stanford in 2019 under the supervision of Professor Allison Okamura. Her research focuses on creating more robust and adaptable soft robots including soft robots inspired by plants, which grow to explore their environments and build structures, and soft devices that help people feel virtual worlds to allow for more seamless human-robot interaction. Outside of academics, she enjoys playing board games and going on hikes.

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Margaret Coad is an assistant professor of aerospace and mechanical engineering at the University of Notre Dame. She conducts research on design, modeling, and control of innovative robotic systems to improve human health, safety, and productivity; she also teaches courses in robotics and soft robotics. Prior to joining Notre Dame, she completed her Ph. D. degree in 2021 and M. S. degree in 2017 in mechanical engineering at Stanford University under the direction of Professor Allison Okamura, and her B. S. degree in 2015 in mechanical engineering at MIT. Outside of academics, she plays ultimate frisbee and sings in a choir. *mcoad@nd.edu