Abstract

This article introduces Pyro, an open source Python Robotics toolkit for exploring topics in AI and robotics. We present key abstractions that allow Pyro controllers to run unchanged on a variety of real and simulated robots. We demonstrate Pyro’s use in a set of curricular modules. We then describe how Pyro can provide a smooth transition for the student from symbolic agents to real-world robots, which significantly reduces the cost of learning to use robots. Finally we show how Pyro has been successfully integrated into existing AI and robotics courses.

Keywords: AI education, robotics, Python, integrated programming environment, toolkit

1 Introduction

In this article we present Pyro, an open source, Python-based programming environment for exploring robotics and artificial intelligence. Pyro (which stands for Python Robotics) enables users to easily write sophisticated AI programs in Python to control a variety of robots and agents. Pyro provides a high-level interface to robots relieving the user from low-level, robot-specific details. Further, robot programs written in Pyro can be used to control several different kinds of robots without any modifications. Pyro has already been successfully used in a number of undergraduate and graduate-level AI courses at several different institutions. In this article, we will introduce Pyro as a programming environment for teaching robotics and AI. To find out more about the underlying design principles and evolution of Pyro see [2].

One of the main goals of Pyro is to reduce the cost of learning to program robots and AI agents. The last decade has seen a proliferation of mobile robot platforms that has led to their introduction in undergraduate and graduate-level AI curricula. However, each robot comes with its own, often proprietary, programming environment or API. Thus, the cost of learning to program robots includes the overhead of learning the specific robot’s programming paradigm, and, in many cases, the programming environment. Despite the trend towards low-cost robot platforms, this overhead serves as a barrier against the pedagogical aims of learning to build AI-based robot agents. Pyro solves this problem by introducing generic robot abstractions that are uniform across a number of robot platforms regardless of their size or morphology. This significantly reduces the cost of learning to program robots and makes robotics more accessible to students. Pyro’s abstractions, much like the abstractions provided in high-level programming languages, provide a robot-independent programming interface so that programs, once written in Pyro, can control...
several different kinds of robots using the same code. The current version of Pyro supports the Khepera robot [11], the Pioneer robot [1], the Sony AIBO robot [16], and dozens of other robots in simulation.

All Pyro programs are written in the Python programming language. Python is a relatively new programming language that is quite powerful and embodies several modern programming paradigms. Yet, it is an easy programming language to learn for students and instructors alike. One of the reasons Pyro was developed in Python was to take advantage of the support available in the language for the re-use of existing code. This enables easy integration of existing robot API's, as well as existing libraries of AI code. For example, any code written in C/C++ can be used from within Python code. We have taken advantage of this feature to integrate several existing robot API's as well as existing API's for AI modeling (such as self-organizing maps, and tools for image processing).

Pyro comes integrated with several existing robot simulators (including Robocup Soccer [6], Aria [1], Player/Stage [5], and Gazebo, a newer 3D simulator [7]). Figure 1 shows Pyro running a wander program on a Pioneer robot in the Gazebo simulator. Schools that do not currently own robot platforms can still make use of Pyro by introducing robot programming in their courses through the use of the integrated simulators. Even when an institution owns robots, simulators can be used by students to effectively test and debug programs before they are run on actual robots.

We have developed extensive materials that can be used by instructors to teach robot programming to students. The materials include beginner's tutorials, examples of robot programming paradigms, and several AI modules (such as neural networks and evolutionary computation) that can also be used for doing advanced research in AI. We are continuously adding more modules. Plans are already under way to integrate the AI modules available (in Python) from Russell and Norvig's AI text [15].

Pyro is an open source project. We are committed to the inclusion of contributed materials and code that enhances the functionality of Pyro. We are also committed to adding support for more robot platforms as the robots and their API's become available. Currently, work is under way to integrate support for the low-cost Hemisson robot [8], and also the ER1 robot [14] platforms.

In what follows, we provide a quick first look at writing robot programs in Pyro. This is followed by an overview of the curricular materials currently available and a few more examples. Next we describe how Pyro has been integrated into various courses at different institutions. We will conclude by showing how...
from pyro.brain import Brain

class FollowBrain(Brain):
    def setup(self):
        self.follow = 0
    def step(self):
        if(min(self.get('/robot/range/front-all/value')) < 0.5):
            print "wall ahead, turn right"
            self.robot.move(0, -0.2)
        elif(self.follow and min(self.get('/robot/range/front-left/value')) < 0.55):
            print "following, adjust right"
            self.robot.move(0.2, -0.05)
        elif(self.follow and min(self.get('/robot/range/back-left/value')) < 0.55):
            print "following, adjust left"
            self.robot.move(0.2, 0.05)
        elif(min(self.get('/robot/range/left/value')) < 0.9):
            print "following"
            self.follow = 1
            self.robot.move(0.2, 0)
        else:
            print "looking for wall"
            self.follow = 0
            self.robot.move(0.5, 0.0)
    def INIT(engine):
        return FollowBrain('FollowBrain', engine)

Figure 2: A platform-independent wall following program in Pyro

Pyro can also be used for developing other, non-robotic, agents using existing AI libraries.

2 A Pyro example

In this section we present a simple wall following program to demonstrate the unified framework that Pyro provides for using the same control program across many different robot platforms. This type of basic controller is an example of reactive control where the robot maintains very limited state information and primarily determines its actions based on its current sensor readings. This form of control is normally the first control method introduced to students learning robotics.

The program shown in Figure 2 is written in an object-oriented style, and creates a class called FollowBrain that inherits from a Pyro class called Brain (Figure 2, line 2). A Pyro brain is required to have a step method (line 5) that implements the decision procedure and is executed on every control cycle (which occur about 10 times a second). A Pyro brain may also have a setup method (line 3) that is called when the brain is instantiated and can be used to initialize class variables.

The brain shown in Figure 2 always tries to follow walls on its left side. On each control step, it first queries the range sensors on its front and then its left side. If the front sensors indicate that the robot is approaching something, then the robot turns right so as to align its left side with the wall. Once it senses that its left sensors are close enough to the wall, then it sets its class variable self.follow to be true and goes straight. When self.follow is true, the robot makes small adjustments to try stay aligned with the wall, which are based on readings from its front-left and back-left range sensors. Otherwise, if the robot is not sensing a wall on its left, it sets its class variable to false and goes straight until it encounters a wall.

It is not crucial to understand all of the details of this Pyro program, however, it is important to recognize how Pyro’s abstractions are used to create a platform-independent implementation. One of the key ideas underlying the design of Pyro is the use of abstractions that make the writing of basic robot behaviors independent of the type, size, weight, and shape of a robot. Consider writing a robot controller for wall following that would work on a Pioneer robot (24-inch diameter, 50-lbs weight) and also on a Khepera robot (2.5-inch diameter, 3-ounces weight) as well as on a simulated robot. Figure 3 illustrates the vast difference in size between the Khepera and the Pioneer robots. The following key abstractions were essential in achieving
Figure 3: Two very different robot platforms, the tiny Khepera and the much larger Pioneer, for which the same Pyro program from Figure 2 can be used for wall following.

this:

**Range Sensors:** Regardless of the kind of hardware used, IR, sonar, or laser, these sensors are categorized as *range* sensors. Sensors that provide range information can thus be abstracted and used in a control program.

**Robot Units:** Distance information provided by range sensors varies depending on the kind of sensors used. Some sensors provide specific range information, like distance to an obstacle in meters or millimeters. Others simply provide a numeric value where larger values correspond to open space and smaller values imply nearby obstacles. In our abstractions, in addition to the default units provided by the sensors, we have introduced a new measure, *a robot unit*: 1 robot unit is equivalent to the diameter of the robot being controlled.

**Sensor Groups:** Robot morphologies vary from robot to robot. This also affects the way sensors, especially range sensors, are placed on a robot’s body. Additionally, the number and positions of sensors present also varies from platform to platform. For example, a Pioneer3 has 16 sonar range sensors while a Khepera has 8 IR range sensors. In order to relieve a programmer from the burden of keeping track of the number and positions of sensors (and their unique numbering scheme), we have created *sensor groups*: **front**, **left**, **front-left**, etc. Thus, a programmer can simply query a robot to report its front-left sensors in robot units. The values reported will work effectively on any robot, of any size, with any kind of range sensor given appropriate coverage, yet will be scaled to the specific robot being used.

**Motion Control:** Regardless of the kind of drive mechanism available on a robot, from a programmer’s perspective, a robot should be able to move forward, backward, turn, and/or perform a combination of these motions (like moving forward while turning left). We have created the motion control abstraction: *move(translate, rotate)* where movements are given in terms of turning and forward/backward changes. This is designed to work even when a robot has a different wheel organization (such as multi-wheed, omni-directional abilities) or four legs (as with the AIBO). As in the case of range sensor abstractions,
the values given to this command are independent of the specific values expected by the actual motor
drivers. A programmer only specifies values in a range [-1.0,1.0].

The wall following program in Figure 2 illustrates the use of all of the above abstractions. Each case of
the if statement (starting on line 6) queries the robot’s range sensors based on a specific sensor group and
checks for range values in terms of robot units. For example, the robot will respond to obstacles in the front
when they are within half a robot unit and the robot is considered to be following a wall when it is within
0.9 robot units on its left side. In addition, each case of the if statement uses the abstract move command
to control the robot’s next action.

Given this first glimpse of Pyro, the next section gives an overview of the curricular modules available
within Pyro and provides several more examples of Pyro’s capabilities.

3 Curricular materials

The Pyro library includes several modules that enable the exploration of robot control paradigms, robot
learning, robot vision, localization and mapping, and multi-agent robotics. Within robot control paradigms
there are several modules: sequential control using finite state machines, subsumption architecture, and
fuzzy logic control. The learning modules provide an extensive coverage of various kinds of artificial neu-
ral networks: feed-forward networks, recurrent networks, self-organizing maps, etc. Additionally we also
have modules for evolutionary systems, including genetic algorithms, and genetic programming. The vision
modules provide a library of the most commonly used filters and vision algorithms enabling students to
concentrate on the uses of vision in robot control. The entire library is open source, and can be used by
students to learn about the implementations of all the modules themselves. We have also provided tutorial-
level educational materials for all of the modules. This enables instructors to tailor the use of Pyro for
many different curricular situations. In the remainder of this section, we provide two more examples of Pyro
programs written using the available libraries.

3.1 Example of sequential control

In order to create more complex robot controllers, it is useful to be able to group low-level robot com-
mands into logical units, often called behaviors. Each behavior is triggered by a particular condition in the
environment, and responds appropriately. Once the initiating condition has been addressed, the current
behavior can pass control off to another behavior. One straight-forward method of implementing this style
of behavior-based control is through finite state machines (FSMs). Each state in the FSM represents a robot
behavior. Using a FSM you can build up a graph of states to go in and out of, sequencing the order of states
into a “plan”.

To illustrate this style of robot control, we can implement a simplified version of a recycling robot. We
demonstrate this using a simulated Pioneer robot with a gripper and a blobfinder. The cans are represented
as randomly positioned red pucks in a circular environment without obstacles. Once the robot has picked
up a puck, it immediately stores it, and moves on to finding more pucks.

The robot begins in the state locatePuck. While in the state locatePuck it rotates, looking for a red
blob. As soon as one is found it goes into state approachPuck to move toward the closest visible puck. If
for some reason the robot loses sight of the puck, it will go back to the state locatePuck. Once the robot is
positioned with its gripper around the puck, it goes to the state grabPuck to pick it up and store it. Then
it will return to the state locatePuck to search again. The state locatePuck keeps track of how long it
searches on each activation of the state. If the robot has done a complete rotation and not seen any pucks,
it goes to the state done and stops moving.

Figure 4 shows the definition of the locatePuck state for this FSM brain. Each state in a FSM must
implement the step method, which is called on every control cycle. States use the goto method to transition
to other states. The optional onActivate method may be used to initialize class variables.
class locatePuck(State):
    def onActivate(self):
        self.searches = 0  # counter for number of rotations
    def step(self):
        redBlobs = self.robot.get('robot/blobfinder/data')[1][0]
        if len(redBlobs) != 0:
            self.robot.move(0, 0)
            print "found a puck!"
            self.goto('approachPuck')
        elif self.searches > 275:
            print "found all pucks"
            self.goto('done')
        else:
            print "searching for a puck"
            self.searches += 1  # update counter
            self.robot.move(0, 0.2)

Figure 4: The implementation of the locatePuck behavior in a FSM-style Pyro program.

Figure 5: A Pioneer robot, controlled by a finite state machine Pyro program, gathering pucks in the Player/Stage simulator. The small box to the left of the robot represents the blob camera data.
Figure 6: In the background, an AIBO robot is shown under the control of Pyro over a wireless network connection. In the foreground, the robot’s raw image (left) is shown next to a processed image (right).

Figure 5 shows a simulated robot as it first begins searching for pucks (A), as it closes in on a particular puck (B), after it has grabbed the puck (C), and as it is pursuing a new puck (D). This style of sequential control is a very effective method of implementing complex robot behaviors.

3.2 Example of vision processing
To explore topics in computer vision, Pyro also comes with camera and image processing modules. Students can write Python programs to implement vision algorithms, such as color histograms, motion detection, object tracking, edge detection, etc. However, Python is currently too slow for this code to be used in real time. To alleviate this problem, we have developed a method such that the low-level vision code is written in C++ but the students can interactively use this code to build layers of filters in Pyro. Thus, students can develop the computationally expensive code in C++, and still have the high-level, interactive interface of Python. For example, in the background of Figure 6, a Sony AIBO robot is looking at a ball. The foreground of Figure 6 shows the raw image on the left and a image-processed view on the right. The processed image has had three filters applied to it: color matching, supercolor, and blob segmentation. The color matching filter marks all pixels in an image that are within a threshold of a given red/green/blue color triplet. The supercolor filter magnifies the differences between a given color and the others. For example, the supercolor red filter makes reddish pixels more red, and the others more black. Finally, the blob segmentation filter connects adjacent like-colored pixels into regions, and returns the regions sorted by area. Figure 6 shows the ball as the largest matching region by drawing a bounding box around it (foreground, right). All of these filters can be applied to the raw image by selecting them from a menu or by programmatically selecting them from a Pyro brain. Once the position of the bounding box is known, the robot can then be programmed to look or move toward the ball.

4 Integrating Pyro into the curriculum: From agents to robots
Teaching artificial intelligence as a coherent subject can be a challenging task. AI is already filled with a wide spectrum of ideas and methodologies that run the gamut from logic to evolution, from information theory to perception. Surely, the idea of incorporating even a bit of robotics would cause an AI course to explode, spewing predicates, symbols, and rules in all directions, right? Actually, we think that including robotics in the standard AI course, if done appropriately, can actually help. We recognize that not everyone thinks that robots in the AI classroom is a good idea. Marvin Minsky recently was quoted as being appalled at the amount of time that students were wasting on “soldering and repairing” such “stupid little robots”
Figure 7: Simple Vacuum Cleaner World (after Russell and Norvig, 2003). This simulation, itself, was written in less than 100 lines of Python code, including the graphics, thread, and socket code. Although we have other AI-based simulations, such as Konane (a Hawaiian checkers game), students can also write their own simulations and games fairly easily.

```python
function Reflex-Vacuum-Agent([location, status]) returns an action
    if status = Dirty then return Suck
    else if location = A then return Right
    else if location = B return Left
```

Figure 8: Russell and Norvig’s reflex vacuum agent [15] figure 2.8 page 46.

(Wired News, May 13, 2003). Although we feel his criticisms were largely misguided, we also can appreciate appropriate efficacy in the classroom. Here, we suggest the use of pre-built, commercial robots.

In addition to having access to affordable robots, another trend over the last decade also helped make robotics a viable topic in AI. In 1995, Russell and Norvig published their first edition of *AI: A Modern Approach* which used an agent-based perspective for exploring all of artificial intelligence. This approach was, to many, a more effective technique of weaving together the disparate topics of AI than past attempts. This resulted in a successful textbook that has been adopted by many colleges and universities, and which has generated a second edition [15].

Approaching AI in the classroom from the perspective of an agent is a simple but effective methodology. A common approach is to introduce the ideas of the agent and its environment. Agents are in turn composed of sensors and actuators. The details of the sensors and actuators are usually downplayed, if not completely ignored in an AI class. In robotics, of course, these are the core concepts. However, focusing on the sensors and actuators early in an AI class can bring to light important issues in AI:

- What happens if a sensor is not accurate?
- What happens if the world changes after a sensor is read?
- How does the robot know where it is?
- What happens if a robot doesn’t move exactly the way it was supposed to?

Having such issues highlighted early in the semester can make it easier to talk about why one AI technique might be more appropriate than another for a given problem. Of course, having an implementation of an agent-based algorithm can help students by providing a concrete example with which to make these issues more salient. It will also allow them to transition from the symbolic domains of agents to the real-world domains of robots.

Consider the vacuum world shown in Figure 7 and the simple reflex agent controller shown in Figure 8. The algorithm describes a robot vacuuming cleaner that can suck up dirt and move between two locations,
from pyro.brain import Brain

class SimpleBrain(Brain):
    def ReflexVacuumAgent(self, location, status):
        if status == "dirty": return "suck"
        elif location == "A": return "right"
        elif location == "B": return "left"
    def step(self):
        # ask the robot for perceptions:
        location = self.get("robot/location")
        status = self.get("robot/status")
        # call the agent program
        action = self.ReflexVacuumAgent(location, status)
        # make the move:
        self.robot.move(action)
    def INIT(engine):
        return SimpleBrain('My Vacuum Robot Brain', engine)

Figure 9: A Pyro program to clean up two rooms using a simple reflex brain. After Russell and Norvig (2003), page 46.

A and B. Now consider the code to implement it on as a robot within Pyro. Of course, building such a robot for such a simple example would not be worthwhile. However, if the students could easily have access to such a robot, and the concepts would carry over into the rest of the course, then it could be a valuable concrete example from which one can build more complex concepts.

In this Pyro variation, the perceptions and actions are represented by symbols. Figure 9 shows that the perceptual value of status is either dirty or clean, the value of location is either A or B, and movements are suck, left and right. However, the methods of accessing the sensors and affecting the motors are identical to those used to interact with real robots. Using Pyro in this manner could be useful for just exploring AI. However, this agent-based symbolic use also prepares the student for exploring any number of other topics in robotics.

Because Pyro allows students to immediately focus on the most abstract, top-down issues in autonomous control, we have been able to incorporate Pyro into a variety of courses. Specifically, at our institutions, the following courses have used Pyro: Introduction to Artificial Intelligence, Cognitive Science, Emergence, Androids: Design & Practice, Developmental Robotics, Mobile Robotics, Robotics II, Senior Theses, and summer research projects for undergraduate students as well as high-school students. To date, we have recorded that Pyro has been used in courses in at least two dozen educational institutions.

Based on our own experiences and from those reported by early adopters of the system, it is clear that wherever in the curriculum robotics is used, Pyro can be used as a laboratory environment. In all of the instances, students are able to successfully write several robot control programs for real and simulated robots. In most instances, students learned Pyro and robot programming by following the tutorial materials we have created. The kinds of exercises and the extent to which Pyro was used varied depending on the course and its focus. The exercises span the entire spectrum of difficulty, ranging from modifying existing robot brains to research-level work in robotics. In one instance, three students from Bryn Mawr College developed a robot Tour Guide [3, 4] that gave tours of the Science Building. Next, we present a couple of sample instantiations of undergraduate AI courses that were modified to include the use of Pyro.

4.1 Pyro in Artificial Intelligence Courses

In this section we present an overview of two versions of an undergraduate junior/senior-level AI course at two similar institutions: Bryn Mawr College and Swarthmore College. Demonstrating how Pyro can be integrated into an upper-level AI course is perhaps the best way to highlight the flexibility available to instructors.

1The students applied for and obtained funding for this project from the Computing Research Association’s (CRA) CREW Program.
At both colleges, the AI course is typically taught every other year. The Bryn Mawr course followed a traditional, agent-oriented approach based on Nilsson’s book [12], while the Swarthmore course had a machine learning focus based on Mitchell’s book[10]. At both colleges, the labs were designed to introduce students to the Python programming language, the tools available within Pyro, and the topics being covered in class. Most labs were relatively short in duration, typically lasting only a week. Some of the labs were designed to allow students to explore a topic in much more depth and lasted two to three weeks. Tables 1 and 2 provide an overview of the two courses.

At Bryn Mawr College, the AI course includes both computer science majors and non-majors. Typically, anywhere from 30-40% of the students in the class are from outside of computer science, most without much prior knowledge of programming. As final projects in the Bryn Mawr class, students had robots learn to do wall following using neural networks, created weather prediction systems using neural nets, wrote game playing programs for Connect Four, Othello, and a Checkers variant that uses chance, and had systems which learned static evaluation functions for Konane. All of these projects used Pyro and/or Python.

At Swarthmore College, the course is intended for computer science majors who have completed both CS1 and CS2. As final projects in the Swarthmore class, the majority of the students chose a task in which the robot would be controlled by a neural network and the weights of the network would be evolved by a genetic...
The most ambitious robot learning project involved a three-way game of tag in which each robot had a unique color: the red robot was chasing the blue robot, the blue robot was chasing the green robot, and the green robot was chasing the red robot. The neural network brain for each robot had the same structure, but the weights were evolved in a separate species of the genetic algorithm. The reason for this was to allow each robot to develop unique strategies. Other robot learning projects from the class included having a robot gather colored pucks scattered randomly throughout the environment, having a robot navigate a PacMan-inspired maze while avoiding a predator robot, and having a robot trying to capture a puck from a protector robot.

Pyro’s infrastructure allowed the students to focus on the most interesting aspects of the project, such as the environment, task, network architecture, etc., without having to worry about the details of how the AI algorithms themselves were implemented. The abstractions provided within Pyro enabled the students to easily integrate various AI modules (neural networks and genetic algorithms, for example) and develop quite sophisticated robot learning projects in a short amount of time (typically two-three weeks).

4.2 Pyro in Robotics Courses

In addition to AI courses, Pyro has been used in AI-based robotics courses at both the undergraduate and graduate level. Topics covered include robot architectures, vision, machine learning (including neural networks and reinforcement learning), mapping and localization, and multi-agent robotics. The course uses Pyro modules for weekly labs, then culminates in a three week project at the end of the term. Student projects include the following:

- **Laser Tag**: Students designed hardware to send and receive infrared signals, then wrote software to make the game-playing robots locate and target each other. Robots were programmed with different strategies to make the game more interesting.

- **Robot Slalom**: Students used computer vision to find gates in a slalom course that ran down a hallway and around corners.

- **Pick Up the Trash**: Students used computer vision to find trash (Styrofoam cups) and recycling (soda cans), then deliver the found items to the appropriate bins (trash can or recycling bin). In two weeks, students were able to complete what had been a competition in the 1994 and 1995 AAAI Robot Competition.

As is evident from the use of Pyro in AI and Robotics courses, Pyro enables students at all levels to do robotics projects that in the past were only feasible by research teams. This, we believe, is one of the biggest pay-offs of Pyro. It brings aspects of current research into the curriculum in an accessible, low-cost manner.

5 Conclusions and Future Directions

The Pyro project is the latest incarnation of our attempts to make the teaching of autonomous mobile robots accessible to students and instructors alike. We have developed a variety of programs, examples, and tutorials for exploring robotics in a top-down fashion, and we are continuing to add new curricular modules. Some of these modules are created by students in the classes, others by the authors, and some by faculty at other institutions who have adopted Pyro. Modules currently under development include multi-agent communication, reinforcement learning, logic, planning, and localization.

We believe that the current state-of-the-art in robot programming is analogous to the era of early digital computers when each manufacturer supported different architectures and programming languages. Regardless of whether a computer is connected to an ink-jet printer or a laser printer, a computer today is capable of printing on any printer device because device drivers are integrated into the system. Similarly, we ought to strive for integrated devices on robots.

Our attempts at discovering useful abstractions are a first and promising step in this direction. We believe that discoveries of generic robot abstractions will, in the long run, lead to a much more widespread use of
robots in education and will provide access to robots to an even wider range of students. Our goal is to reduce the cost of learning to program robots by creating uniform conceptualizations that are independent of specific robot platforms and incorporate them into an already familiar programming paradigm. Conceptualizing uniform robot capabilities presents the biggest challenge: How can the same conceptualization apply to different robots with different capabilities and different programming API’s?

Our approach, which has been successful to date, has been shown to work on a variety of real and simulated robots. We are striving for the write-once/run-anywhere idea: robot programs, once written, can be used to drive vastly different robots without making any changes in the code. This approach leads the students to concentrate more on the modeling of robot brains by allowing them to ignore the intricacies of specific robot hardware. More importantly, we hope that this will allow students to gradually move to more and more sophisticated sensors and controllers. In our experience, this more generalized framework has resulted in a better integration of robot-based laboratory exercises in the AI curriculum. It is not only accessible to beginners, but is also usable as a research environment for our own robot-based modeling.

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