Writing Reusable Code Feedback at Scale with Mixed-Initiative Program Synthesis

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When Writing Feedback on Student Code, Teachers Can Draw on Deep Domain Knowledge

Incorrect Student Code Submissions

Submission 1 ✗

```
@@ -1,6 +1,8 @@
def accumulate(combiner, base, n, term):
    def prtii(combiner, n, term):
        if n==1:
            return term(n)
        return combiner(term(n), prtii(combiner, n-1, term))
    return combiner(base, prtii(combiner, n, term))
```

Submission 2 ✗

```
@@ -1,8 +1,10 @@
def accumulate(combiner, base, n, term):
    value = term(n)
    def find_value(combiner, base, n, term, value):
        if n==1:
            return combiner(base, value)
        else:
            return find_value(combiner, base, n-1, term, comb
    return find_value(combiner, base, n, term, value)
```

Submission 3 ✗

```
@@ -1,7 +1,9 @@
def accumulate(combiner, base, n, term):
```

Teacher Comments

What happens when n is zero? Hint: look at lecture 5's slide

While this he

…but it does not scale.

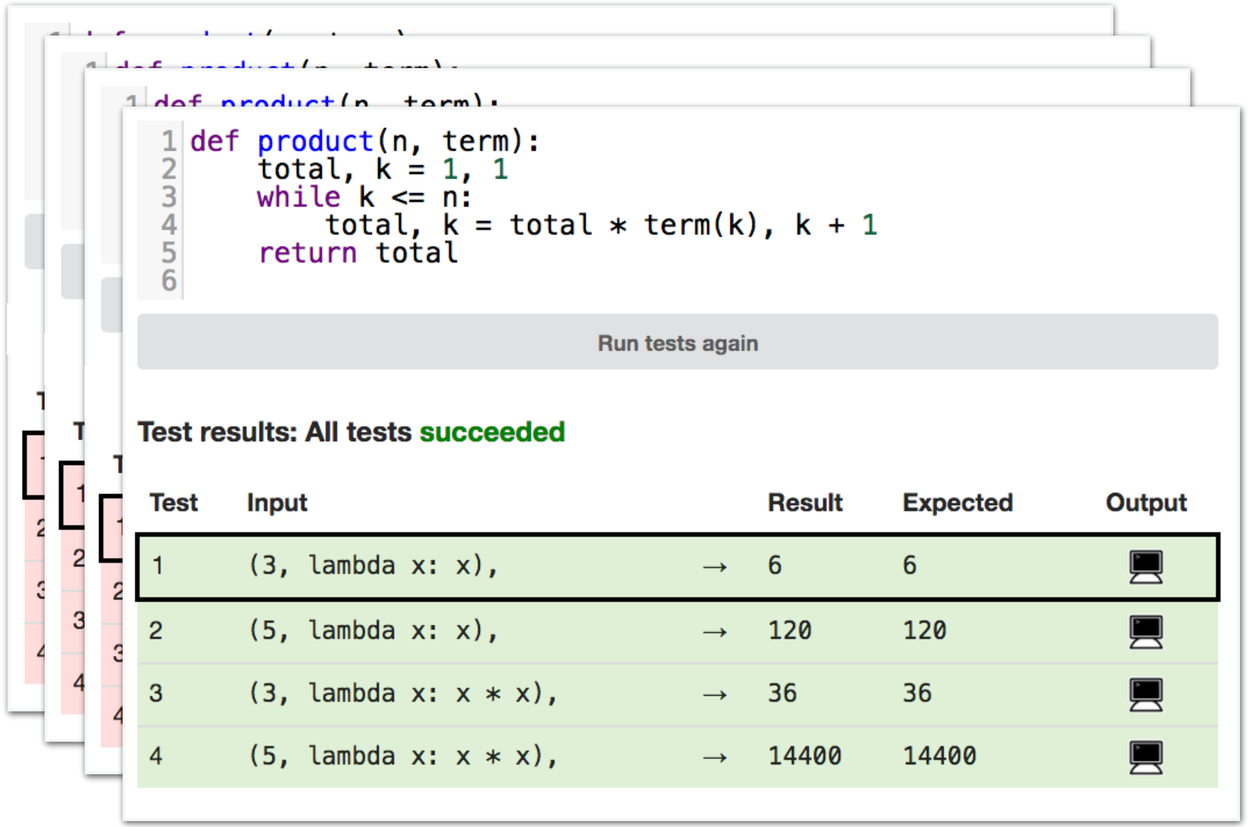
e c

Have you considered what would happen if combiner was se

In lieu of Teacher-Written Feedback, Autograder Shows Test Cases

Student Submission

Test Case Results



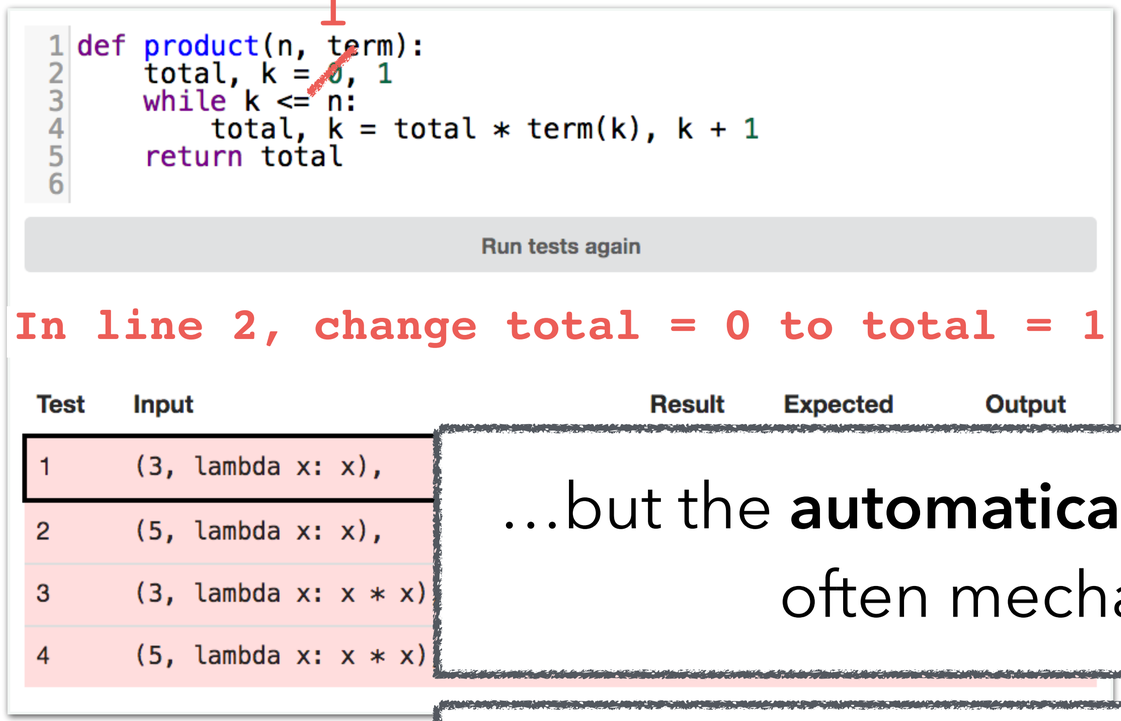
Course Autograder

…but there's still a **gulf of evaluation**.

Program Synthesis Techniques Can Shrink the Gulf by Automatically Finding and Suggesting Bug Fixes for Students

Student Submission

Test Case Results



…but the **automatically generated feedback** is often mechanical, formulaic

Can we combine teachers' deep domain knowledge with program synthesis to **give students better feedback**?

Learning Code Transformations from Pairs of Incorrect and Correct Submissions

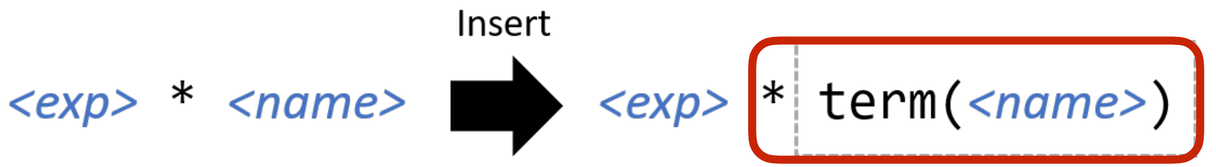
Student 1 fixes iterative solution

```
 def product(n, term):
   total, k = 1, 1
   while k<=n:
-    total = total*k
+    total = total*term(k)
     k = k+1
   return total
```

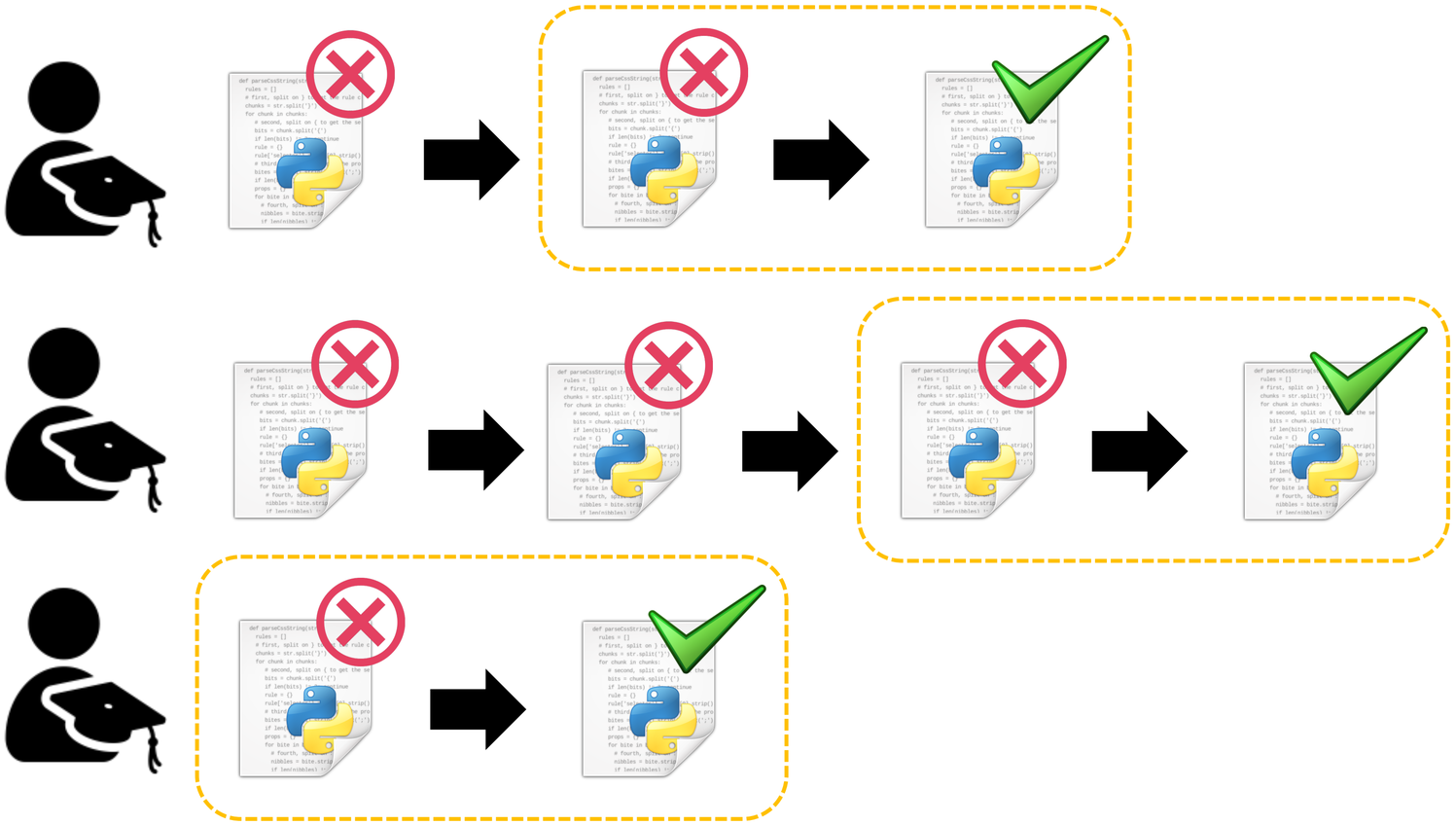
Student 2 fixes recursive solution

```
 def product(n, term):
   if (n==1):
     return 1
-  return product(n-1, term)*n
+  return product(n-1, term)*term(n)
```

Generalized code transformation



Learning Bug-Fixing Code Transformations



We Scale Up a Little Teacher-Written Feedback by Attaching It to Code Transformations

Incorrect Student Code Submissions

Submission 1 ✗

```
@@ -1,6 +1,8 @@
 def accumulate(combiner, base, n, term):
     def prtii(combiner, n, term):
         if n==1:
             return term(n)
         return combiner(term(n), prtii(combiner, n-
+    if n==0:
+        return base
     return combiner(base, prtii(combiner, n, term)
```

Submission 2 ✗

```
@@ -1,8 +1,10 @@
 def accumulate(combiner, base, n, term):
     value = term(n)
+    if n==0:
+        return base
     def find_value(combiner, base, n, term, value):
         if n==1:
             return combiner(base, value)
         else:
             return find_value(combiner, base, n-1,
     return find_value(combiner, base, n, term, valu
```

Code Transformation (add base case)

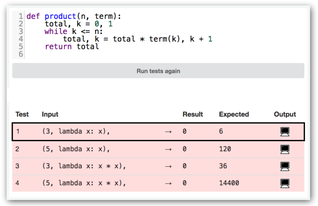
Teacher Comments

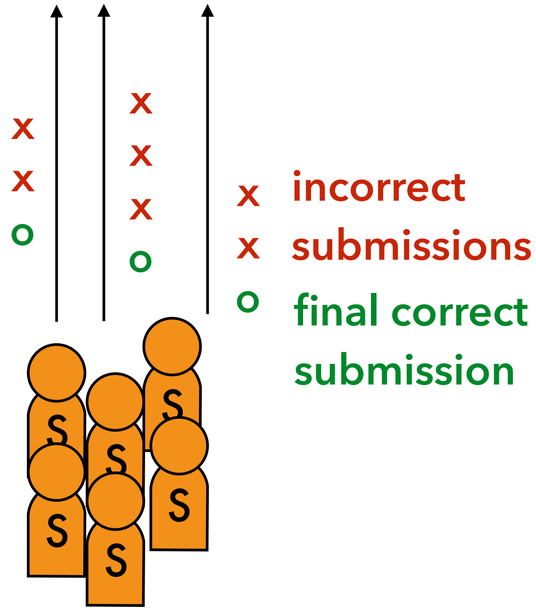
What happens when n is zero?
Hint: look at lecture 5's slides on base cases.

Two Interfaces for Attaching Feedback to Code Transformations

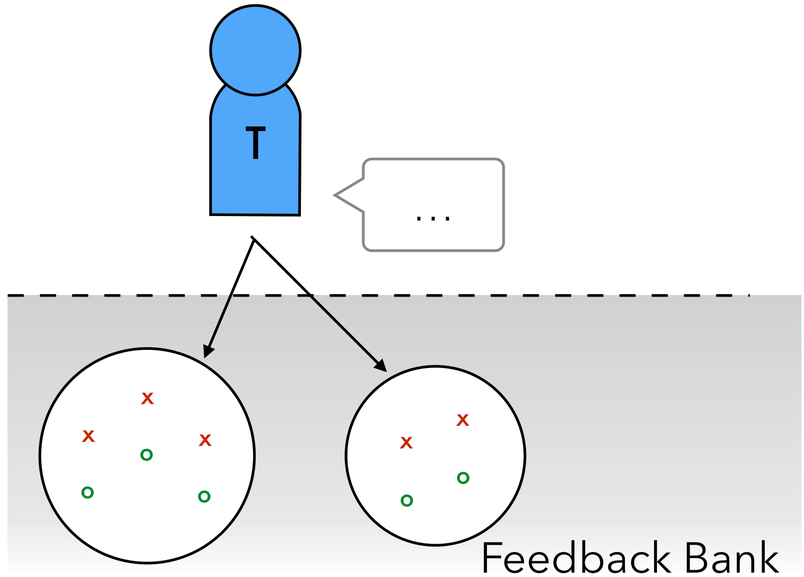
MistakeBrowser: giving feedback on clusters

Learn transformations from Autograder





Collect feedback from teachers

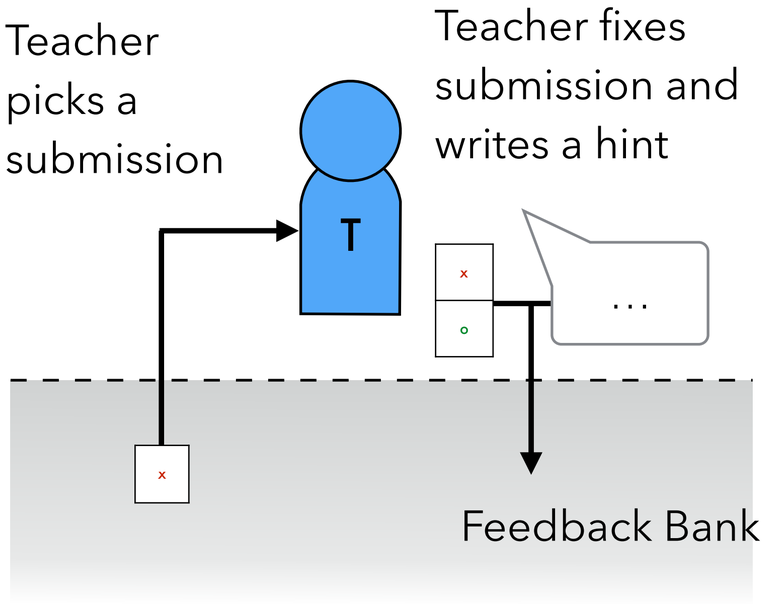


Related Systems: *Divide and Conquer* [ITS14], *AutoStyle* [ITS16]

Two Interfaces for Attaching Feedback to Code Transformations

FixPropagator: attaching feedback to individual fixes

Learns transformations from *and* collect feedback from…



Our Program Synthesis Backend

Refazer *(/hɛ.fa.ˈze(h)/)*
Means “To redo.”

Using *Refazer* [ICSE17] as a backend, our systems
learn bug-fixing code transformations.

Contributions

- An approach for combining human expertise with program synthesis for delivering **reusable, scalable code feedback**

- Implementations of two different systems that use our approach: *FixPropagator*  , *MistakeBrowser* 

- In-lab studies that suggest that the systems fulfill our goals, also inform teachers about common student bugs

Outline

- ~~Related Work~~
- ~~Program Synthesis~~
- Systems
- Evaluation

Related Work

Program Synthesis for Generating Feedback

```
1 def computeDeriv(poly):
2     deriv = []
3     zero = 0
4     if (len(poly) == 1):
5         return deriv
6     for expo in range (0, len(po
7         if (poly[expo] == 0):
8             zero += 1
9         else:
10            deriv.append(poly[ex
11    return deriv
```

(a) Student's solution

The program requires **3** changes:

- In the return statement **return deriv** in **line 5**, replace **deriv** by **[0]**.
- In the comparison expression **(poly[expo] == 0)** in **line 7**, change **(poly[expo] == 0)** to **False**.
- In the expression **range(0, len(poly))** in **line 6**, increment **0** by **1**.

(b) Generated Feedback

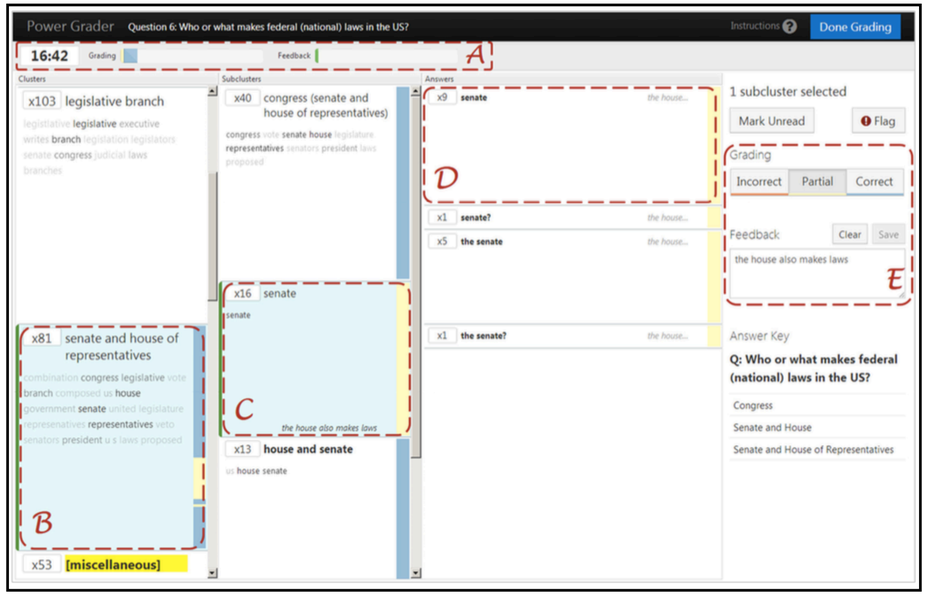
Figure 2. (a) A student's `computeDeriv` solution from the 6.00x discussion board and (b) the feedback generated by our tool on this solution.

AutoGrader [PLDI13]

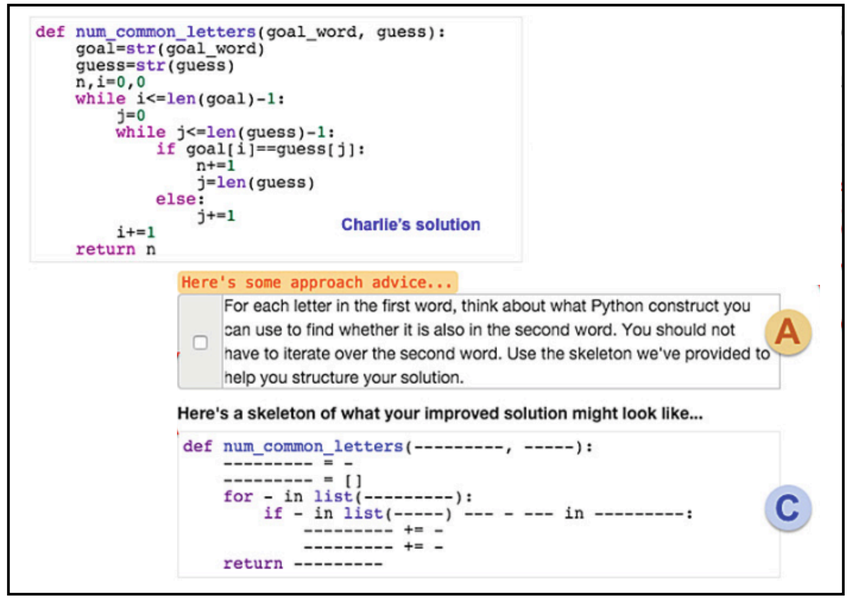
… and beyond CS1 assignments, **AutomataTutor** [TOCHI15], **CodeAssist** [FSE16], …

Related Work

Interfaces for Giving Feedback on Submission Clusters



Divide and Correct [L@S14]



AutoStyle [ITS16]

Program Synthesis

Program synthesis can learn transformations *from demonstrations.*

Full Name	Last Name
Andrew Head	Head
Elena Glassman	*Glassman*
Gustavo Soares	*Soares*
Ryo Sukuzi	*Sukuzi*

Human demonstrates

Synthesized program propagates

Learning Transformations from Demonstrations

Full Name → Last Name

Sources of demonstrations

- students debugging
- teachers correcting student code

Ryo Sukuzi

Submission 1 ✗

```
@@ -1,6 +1,8 @@
 def accumulate(combiner, base, n, term):
     def prtii(combiner, n, term):
         if n==1:
             return term(n)
         return combiner(term(n), prtii(combiner, n-1, term))
     return combiner(base, prtii(com
```

Human demonstrates

Submission 1 ✓

```
@@ -1,6 +1,8 @@
 def accumulate(combiner, base, n, term):
     def prtii(combiner, n, term):
         if n==1:
             return term(n)
         return combiner(term(n), prtii(combiner, n-1, term))
+    if n==0:
+        return base
     return combiner(base, prtii(combiner, n, term))
```

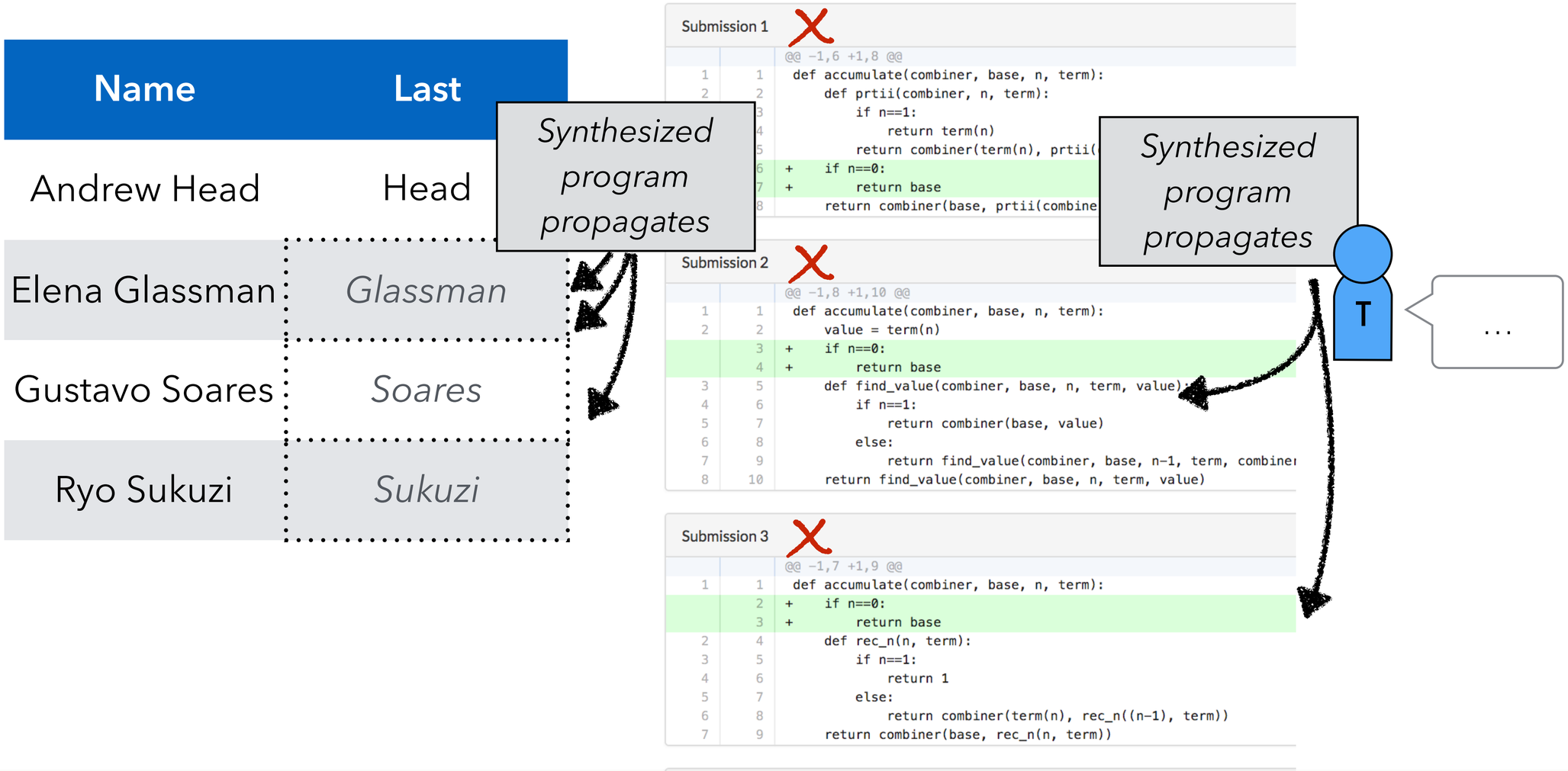
Synthesized transformation:

`Split string on space, return second substring`

Synthesized transformation:

`Before final return statement, insert AST node "if n==0: return base"`

Propagating Transformations



What Bug-Fixing Code Transformations Can Refazer Learn?

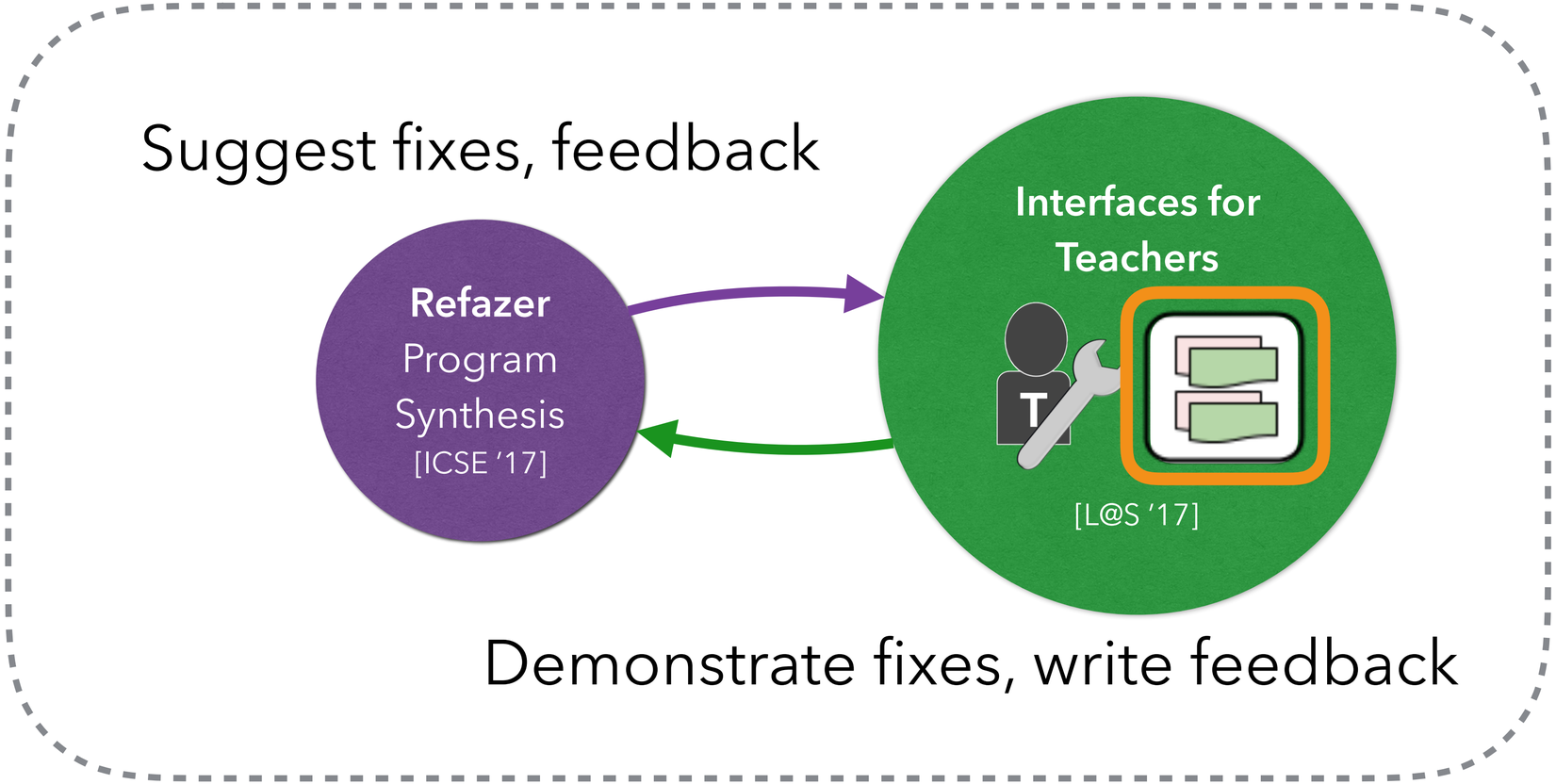
```
1  1  def accumulate(combiner, base, n, term):
2  2      def prtii(combiner, n, term):
3  3          if n==1:
4  4              return term(n)
5  5          return combiner(term(n), prtii(combiner, n-1, term))
   6  +    if n==0:
   7  +        return base
6  8      return combiner(base, prtii(combiner, n, term))
```

Missing base cases…

```
1  1  def repeated(f, n):
2  2      if n==0:
3     -        return f
   3  +        return identity
4  4      else:
5  5          return compose1(f, repeated(f, n-1))
6  6  def compose1(f, g):
7  7      def h(x):
8  8          return f(g(x))
9  9      return h
```

Function substitutions… and so on…

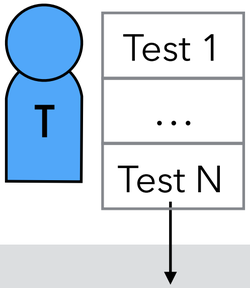
System Design



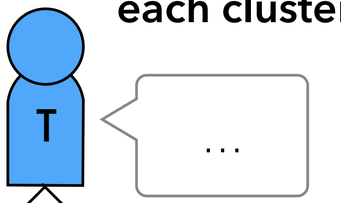
Mixed-initiative workflows

Teacher

Uploads test cases

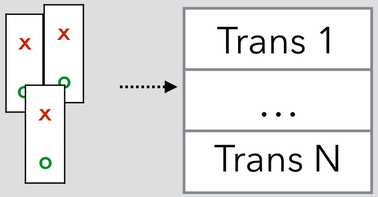


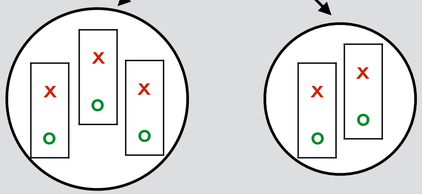
Writes feedback for each cluster



System

Learns transformations



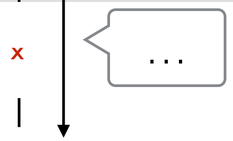


Trans 1 … *Trans N*

Clusters submissions by transformation

Finds transformation that fixes next submission

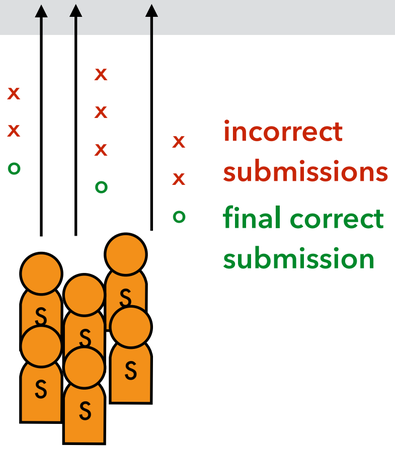
… and returns feedback written for it



Submits incorrect code

… *Next Semester*

Submit code



incorrect submissions

final correct submission

Students

Assignment description

```
Return the product of the first n terms in a sequence.

    n    -- a positive integer
    term -- a function that takes one argument

    >>> product(3, identity) # 1 * 2 * 3
    6
    >>> product(5, identity) # 1 * 2 * 3 * 4 * 5
    120
    >>> product(3, square)   # 1^2 * 2^2 * 3^2
    36
    >>> product(5, square)   # 1^2 * 2^2 * 3^2 * 4^2 * 5^2
    14400
```

Cluster

Cluster 1 41

Examples of applied fix

```
-         return term(n)*term(n-1)
+         return term(n)*product(n-1, term)
```

Submissions

Select all submissions

Submission 1

```
@@ -1,5 +1,5 @@
 def product(n, term):
     if n<=1:
         return 1
     else:
-        return term(n)*term(n-1)
+        return term(n)*product(n-1, term)
```

Test feedback

Input	Expected	Actual
product(5, identity)	120	20

Submission 2

```
@@ -1,9 +1,9 @@
 def product(n, term):
     total = 1
     def a(n):
         if n<=1:
             return 1
         def b(n):
             return term(n)
-        return b(n)*b(n-1)
+        return b(n)*product(n-1, term)
     return a(n)
```

Test feedback

Input	Expected	Actual
product(5, identity)	120	20

Submission 3

```
@@ -1,5 +1,5 @@
 def product(n, term):
     if n==1:
```

Hints

Set Hint Reuse previous hints

Assignment description

```
Return the product of the first n terms in a sequence.

    n    -- a positive integer
    term -- a function that takes one argument

    >>> product(3, identity) # 1 * 2 * 3
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Cluster

Cluster 1 41

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Submissions

Select all submissions

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         if n<=1:
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         def b(n):
             return term(n)
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Test feedback

Input	Expected	Actual
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Submission 3

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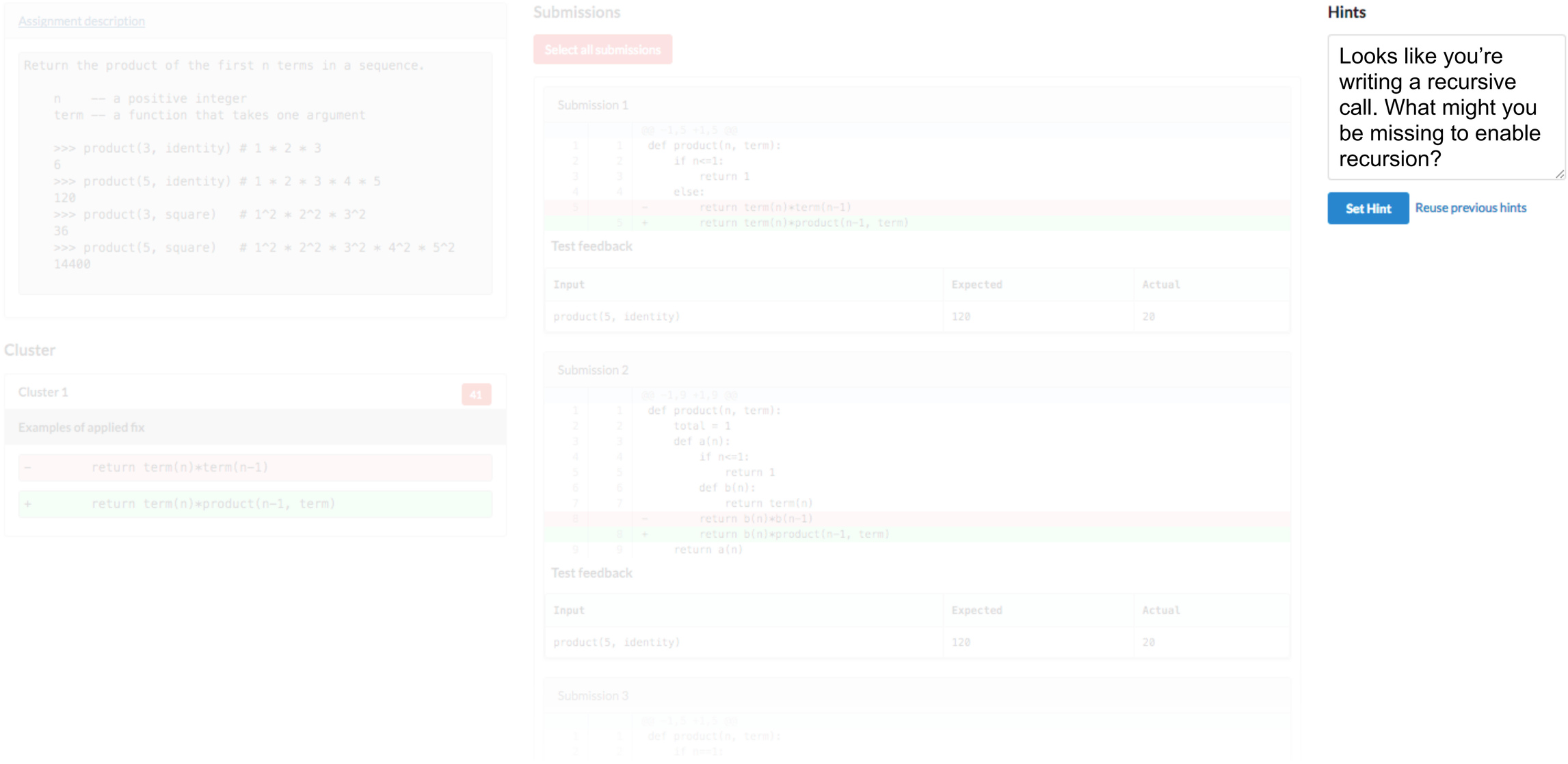
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Submissions
Select all submissions
Submission 1
@@ -1,5 +1,5 @@
def product(n, term):
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Actual
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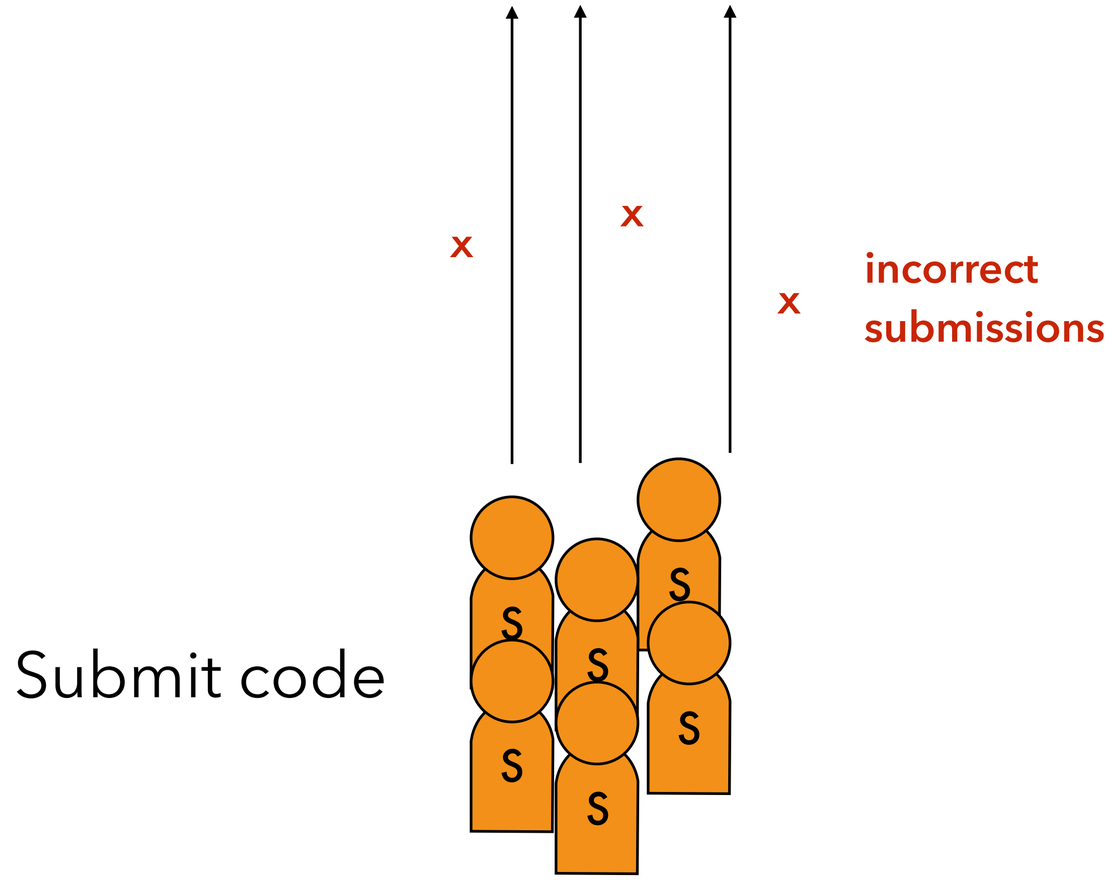
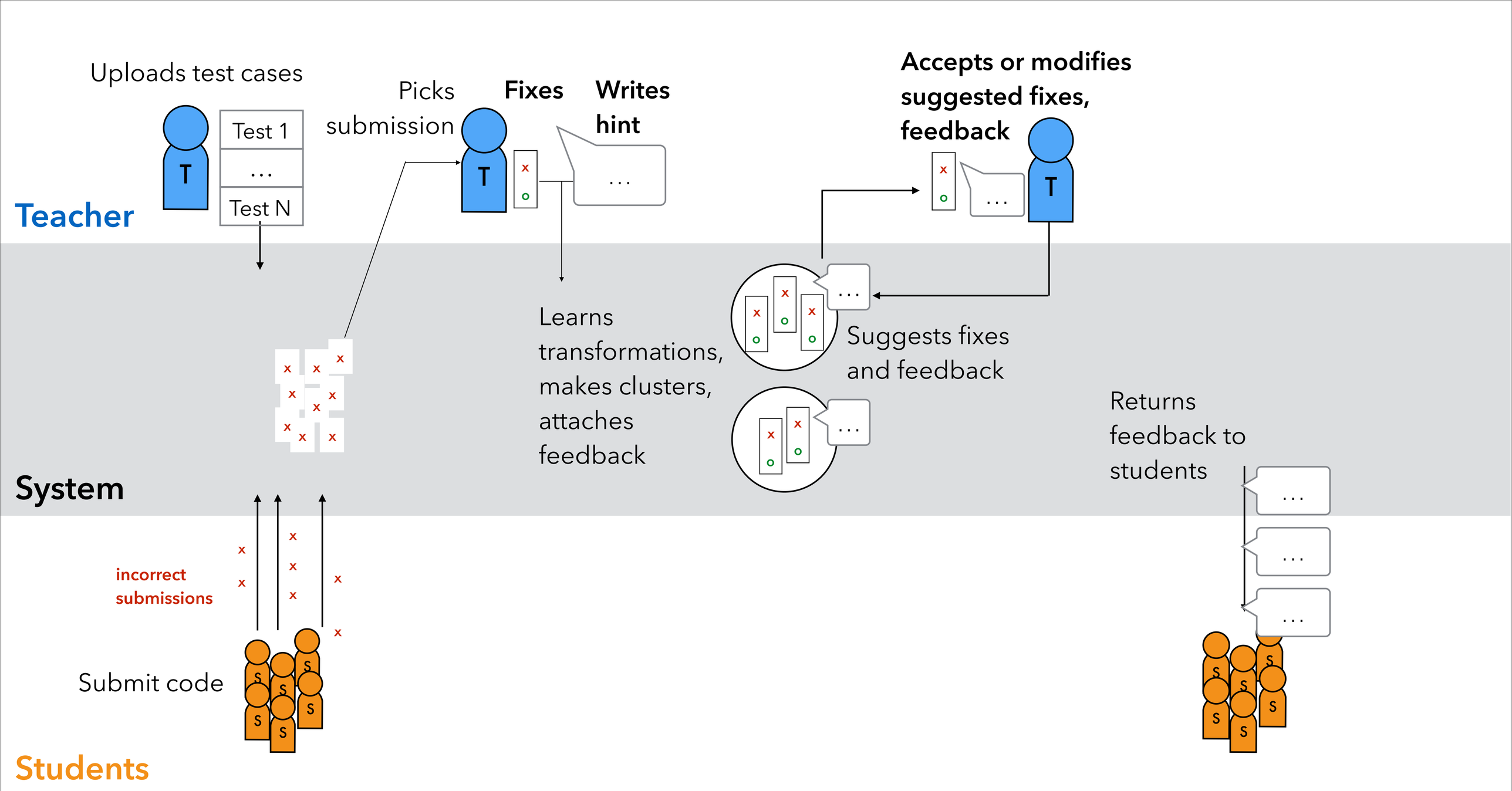
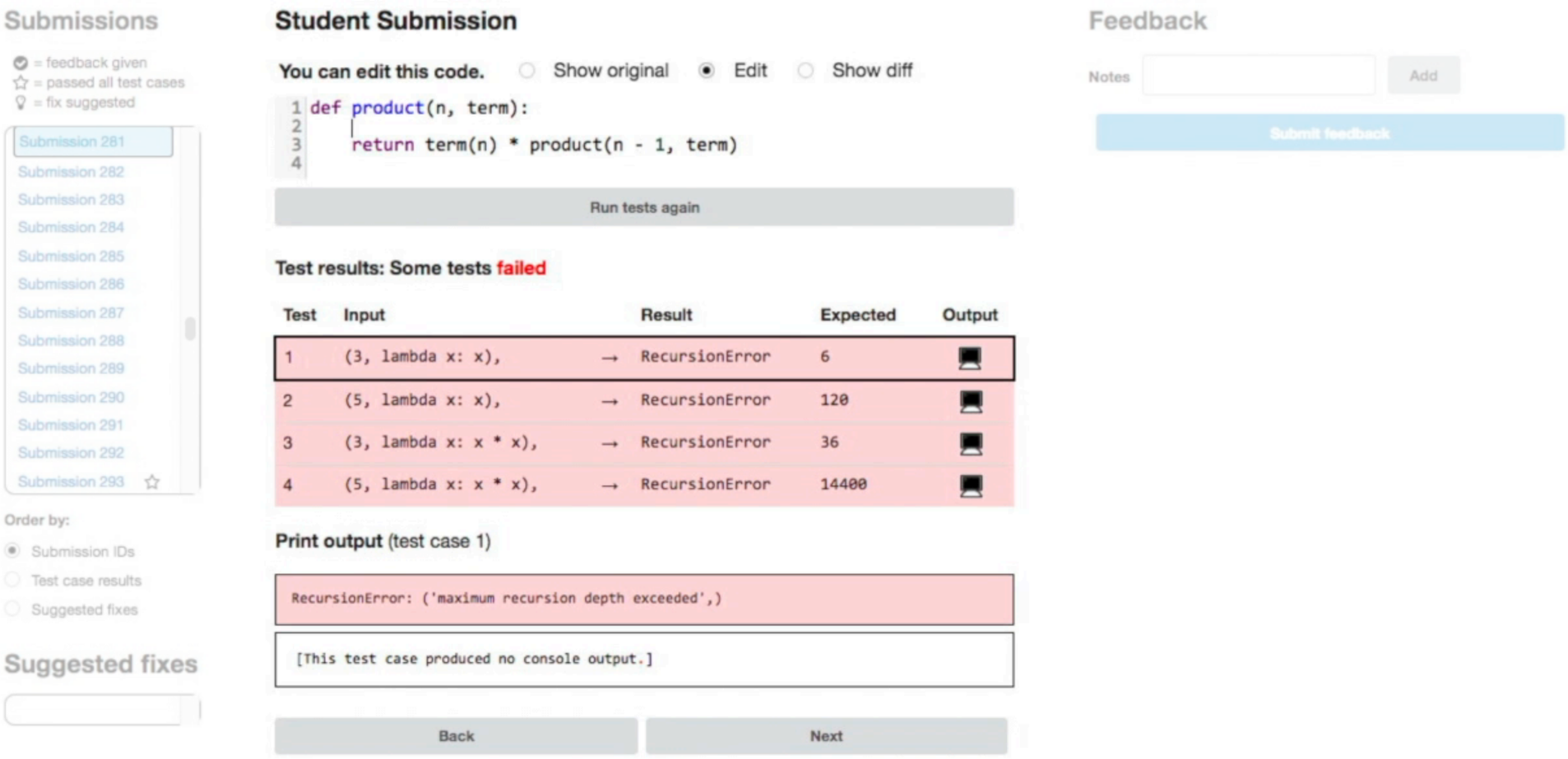
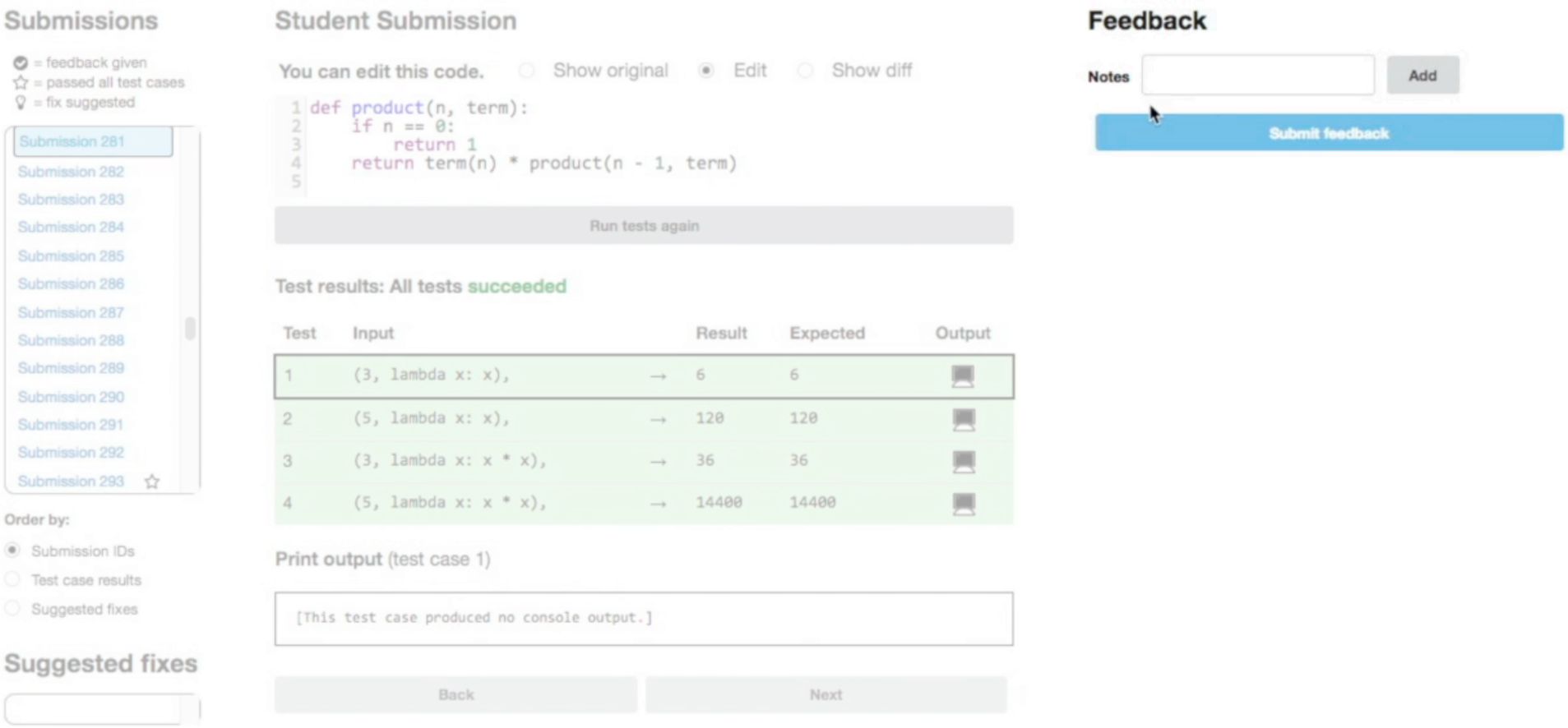
Submission 2
@@ -1,9 +1,9 @@
def product(n, term):
total = 1
def a(n):
if n<=1:
return 1
def b(n):
return term(n)
- return b(n)*b(n-1)
+ return b(n)*product(n-1, term)
return a(n)
Test feedback
Input
Expected
Actual
product(5, identity)
120
20
Submission 3
Hints
Looks like you're writing a recursive call. What might you be missing to enable recursion?
Set Hint
Reuse previous hints

But Not All Classes Have Submission Histories for Hundreds of Students



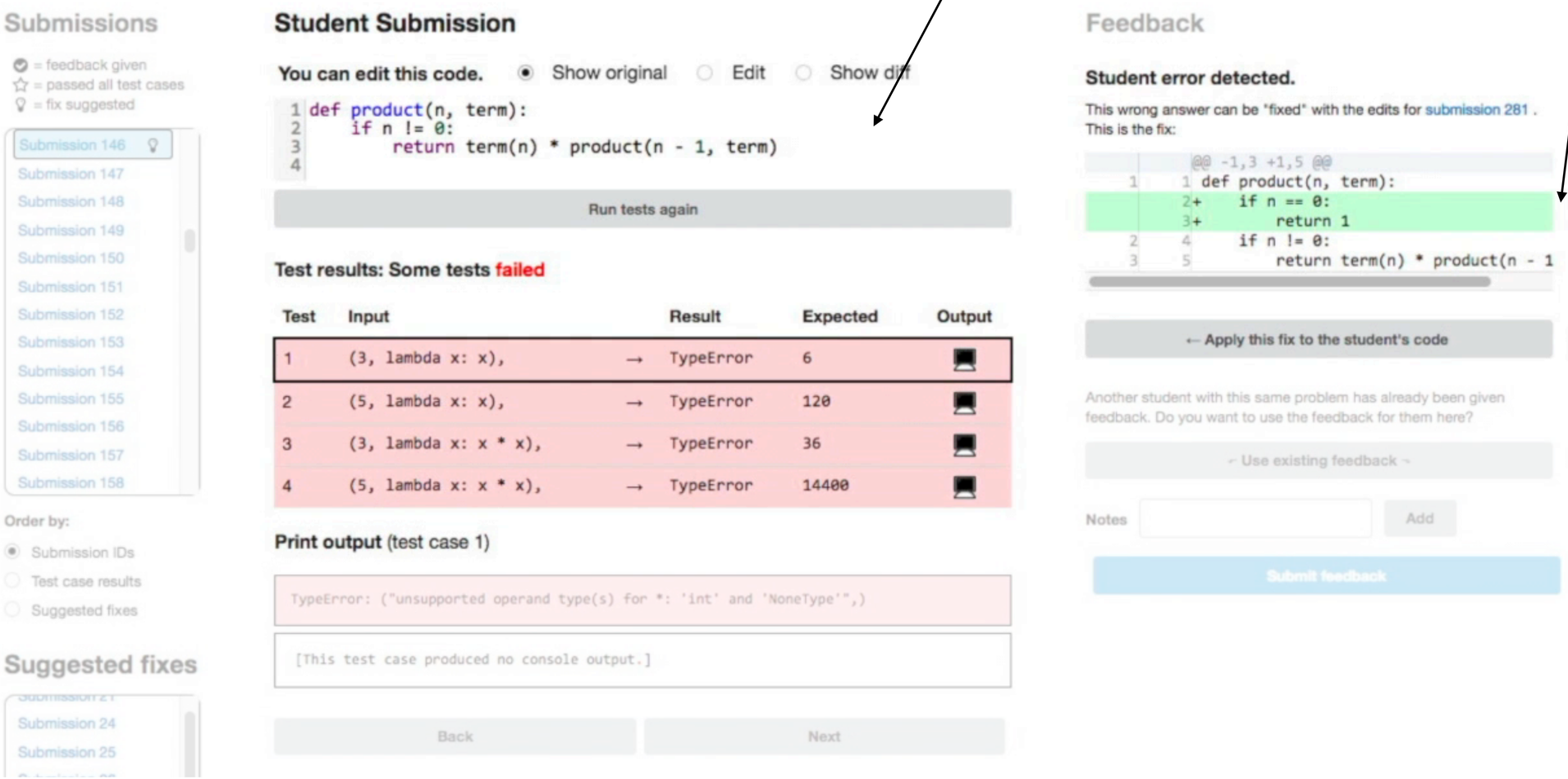

Uploads test cases
Test 1
…
Test N
Picks submission
Fixes
Writes hint
…
Learns transformations, makes clusters, attaches feedback
Accepts or modifies suggested fixes, feedback
…
Suggests fixes and feedback
Returns feedback to students
Teacher
System
incorrect submissions
Submit code
Students

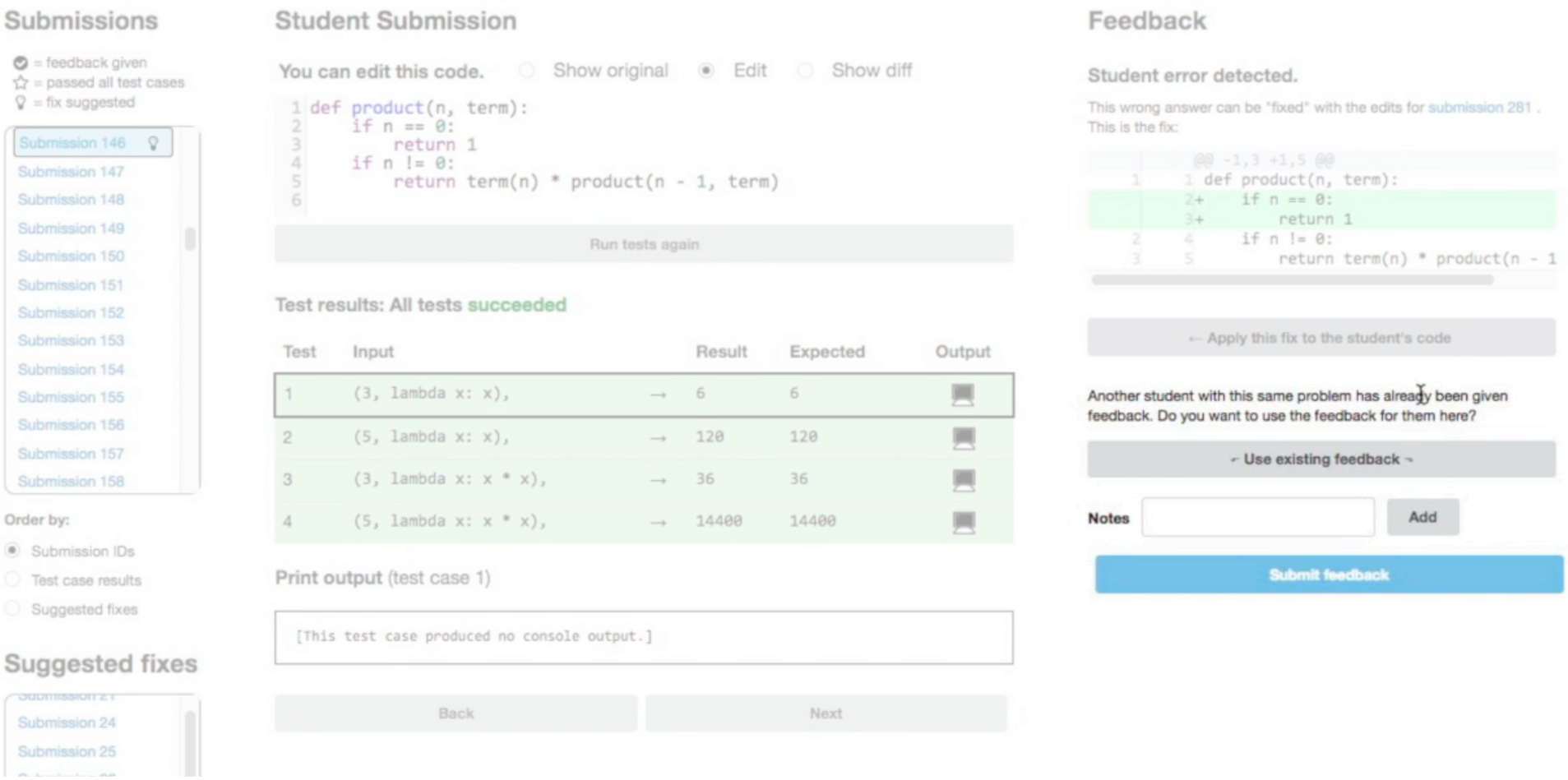

Submissions
= feedback given
= passed all test cases
= fix suggested
Submission 281
Submission 282
Submission 283
Submission 284
Submission 285
Submission 286
Submission 287
Submission 288
Submission 289
Submission 290
Submission 291
Submission 292
Submission 293
Order by:
Submission IDs
Test case results
Suggested fixes
Suggested fixes
Student Submission
You can edit this code.
Show original
Edit
Show diff
1 def product(n, term):
2
3 return term(n) * product(n - 1, term)
4
Run tests again
Test results: Some tests failed
Test Input Result Expected Output
1 (3, lambda x: x), → RecursionError 6
2 (5, lambda x: x), → RecursionError 120
3 (3, lambda x: x * x), → RecursionError 36
4 (5, lambda x: x * x), → RecursionError 14400
Print output (test case 1)
RecursionError: ('maximum recursion depth exceeded',)
[This test case produced no console output.]
Back
Next
Feedback
Notes
Add
Submit feedback

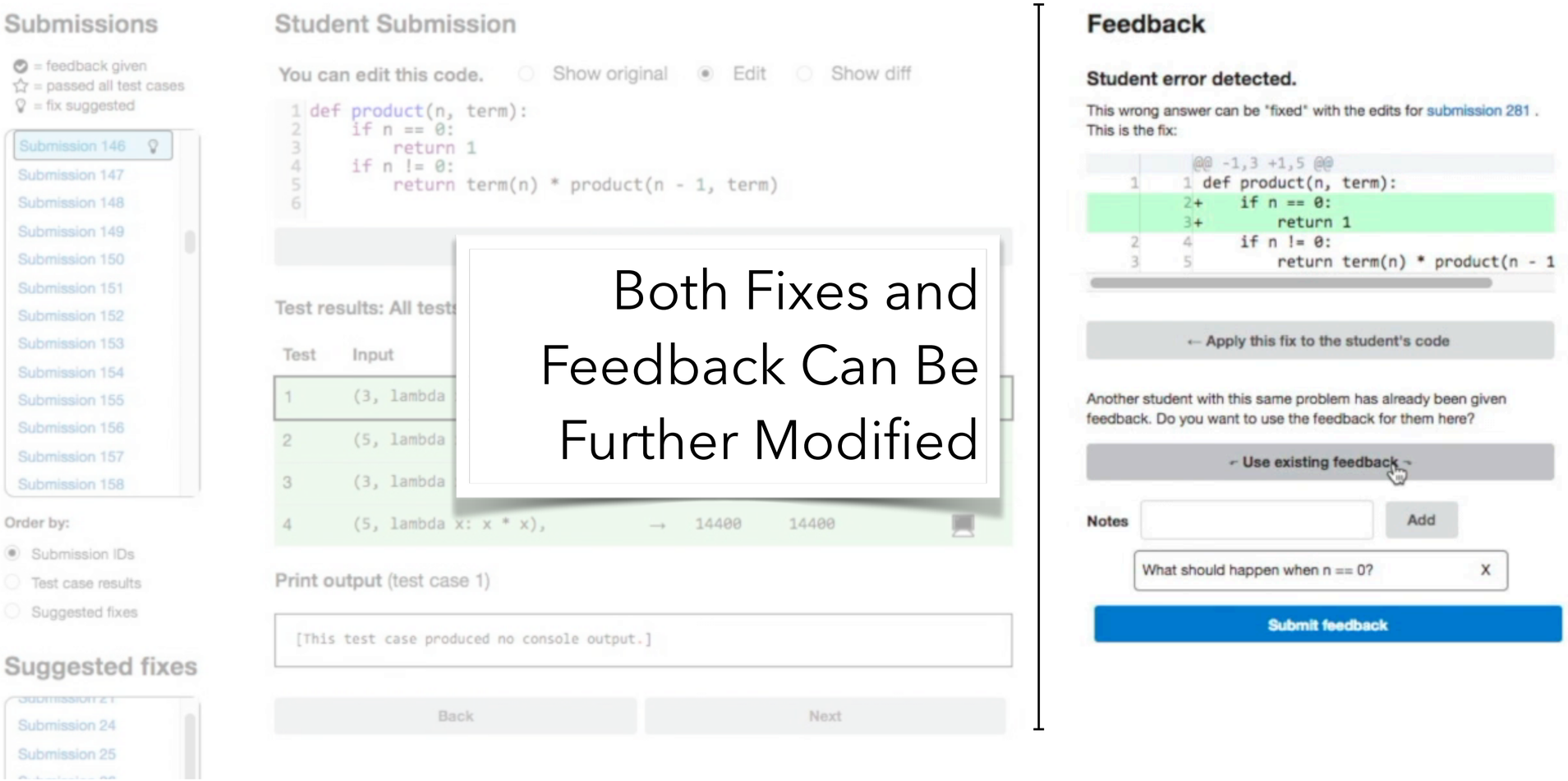

Submissions
= feedback given
= passed all test cases
= fix suggested
Submission 281
Submission 282
Submission 283
Submission 284
Submission 285
Submission 286
Submission 287
Submission 288
Submission 289
Submission 290
Submission 291
Submission 292
Submission 293
Order by:
Submission IDs
Test case results
Suggested fixes
Suggested fixes
Student Submission
You can edit this code.
Show original
Edit
Show diff
1 def product(n, term):
2 if n == 0:
3 return 1
4 return term(n) * product(n - 1, term)
5
Run tests again
Test results: All tests succeeded
Test Input Result Expected Output
1 (3, lambda x: x), → 6 6
2 (5, lambda x: x), → 120 120
3 (3, lambda x: x * x), → 36 36
4 (5, lambda x: x * x), → 14400 14400
Print output (test case 1)
[This test case produced no console output.]
Back
Next
Feedback
Notes
Add
Submit feedback

New Student Submission with Same Bug

Suggested Fix

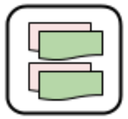



Submissions
= feedback given
= passed all test cases
= fix suggested
Submission 146
Submission 147
Submission 148
Submission 149
Submission 150
Submission 151
Submission 152
Submission 153
Submission 154
Submission 155
Submission 156
Submission 157
Submission 158
Order by:
Submission IDs
Test case results
Suggested fixes
Suggested fixes
Submission 24
Submission 25
Student Submission
You can edit this code.
Show original
Edit
Show diff
def product(n, term):
if n == 0:
return 1
if n != 0:
return term(n) * product(n - 1, term)
Run tests again
Test results: All tests succeeded
Test
Input
Result
Expected
Output
1 (3, lambda x: x), → 6 6
2 (5, lambda x: x), → 120 120
3 (3, lambda x: x * x), → 36 36
4 (5, lambda x: x * x), → 14400 14400
Print output (test case 1)
[This test case produced no console output.]
Back
Next
Feedback
Student error detected.
This wrong answer can be "fixed" with the edits for submission 281 .
This is the fix:
@@ -1,3 +1,5 @@
def product(n, term):
+ if n == 0:
+ return 1
if n != 0:
return term(n) * product(n - 1
← Apply this fix to the student's code
Another student with this same problem has already been given feedback. Do you want to use the feedback for them here?
Use existing feedback
Notes
Add
Submit feedback


Submissions
= feedback given
= passed all test cases
= fix suggested
Submission 146
Submission 147
Submission 148
Submission 149
Submission 150
Submission 151
Submission 152
Submission 153
Submission 154
Submission 155
Submission 156
Submission 157
Submission 158
Order by:
Submission IDs
Test case results
Suggested fixes
Suggested fixes
Submission 24
Submission 25
Student Submission
You can edit this code.
Show original
Edit
Show diff
1 def product(n, term):
2 if n == 0:
3 return 1
4 if n != 0:
5 return term(n) * product(n - 1, term)
6
Test results: All tests
Test
Input
1 (3, lambda
2 (5, lambda
3 (3, lambda
4 (5, lambda x: x * x), → 14400 14400
Print output (test case 1)
[This test case produced no console output.]
Back
Next
Both Fixes and Feedback Can Be Further Modified
Feedback
Student error detected.
This wrong answer can be "fixed" with the edits for submission 281 .
This is the fix:
@@ -1,3 +1,5 @@
1 1 def product(n, term):
2+ if n == 0:
3+ return 1
2 4 if n != 0:
3 5 return term(n) * product(n - 1
← Apply this fix to the student's code
Another student with this same problem has already been given feedback. Do you want to use the feedback for them here?
← Use existing feedback
Notes
Add
What should happen when n == 0?
X
Submit feedback

A Study of the Systems

Participants: Current and former teaching staff from CS1

 MistakeBrowser (*N* = 9)

 FixPropagator (*N* = 8)

Interface Walkthrough (5 mins.)

Main Task (30 mins.): Giving feedback on student submissions
Measurements: Feedback, Manual corrections, Response to feedback recommendations (accepted, changed, rejected), Between-task surveys…

Qualitative Feedback: Survey and Post-interview

1. Can a **few manual corrections fix many** submissions?

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FixPropagator propagates fixes from dozens of corrections to hundreds of submissions.

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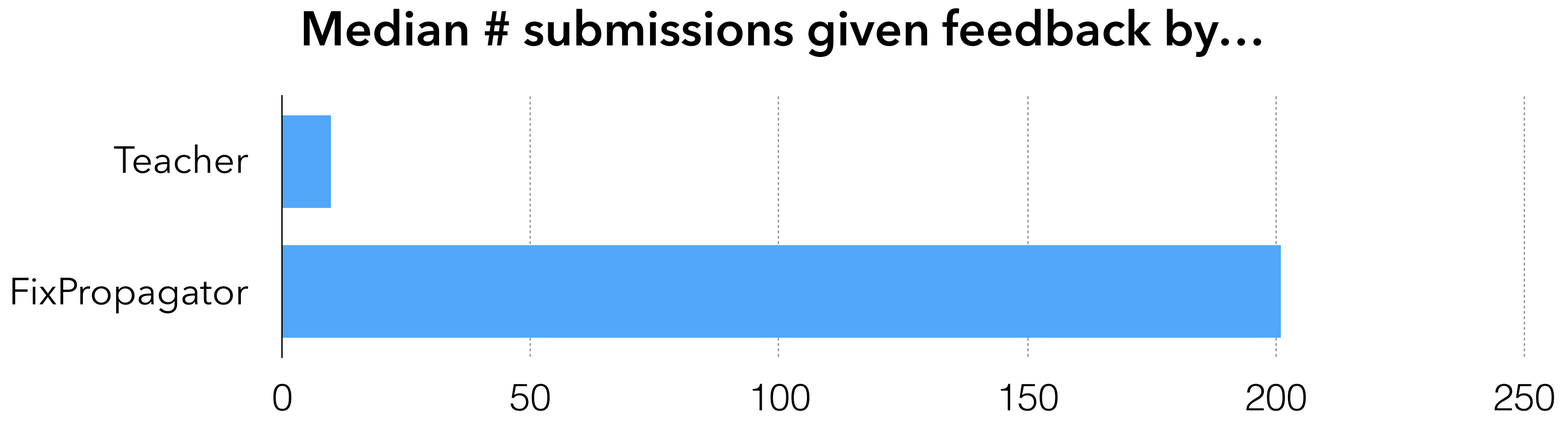
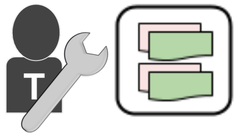


- Fixes were propagated within minutes (*median* = 2m20s, σ = 7m34s for each correction).



2. How often is a teacher's **feedback relevant when it is matched** to other students' submission?

2. How often is a teacher's feedback relevant when it is matched to other students' submission?

Feedback propagated with FixPropagator was correct a majority of the time, but not always.

Teachers reused feedback a median of 20 times, modifying it a median of 6 times (30%).

Generalizable Comment	Non-Generalizable Comment
"Check if you have the product of the correct number of terms."	"Your starting value of *z* should be a function, not an int."

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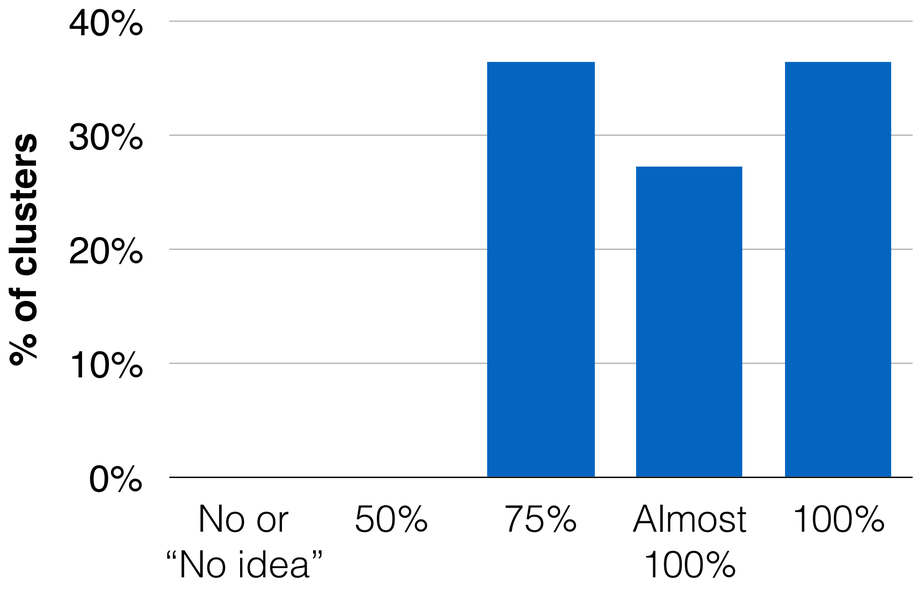


Do these submissions share the same misconception?

Responses for *N* = 11 clusters

Evaluation Questions

1. Can a **few manual corrections fix many** submissions?

   With a median of 10 corrections, FixPropagator suggested fixes for a median of 201 submissions.

2. How often is a teacher's **feedback relevant** when it is matched to another student submission?

   Matched feedback was relevant ~75% of the time.

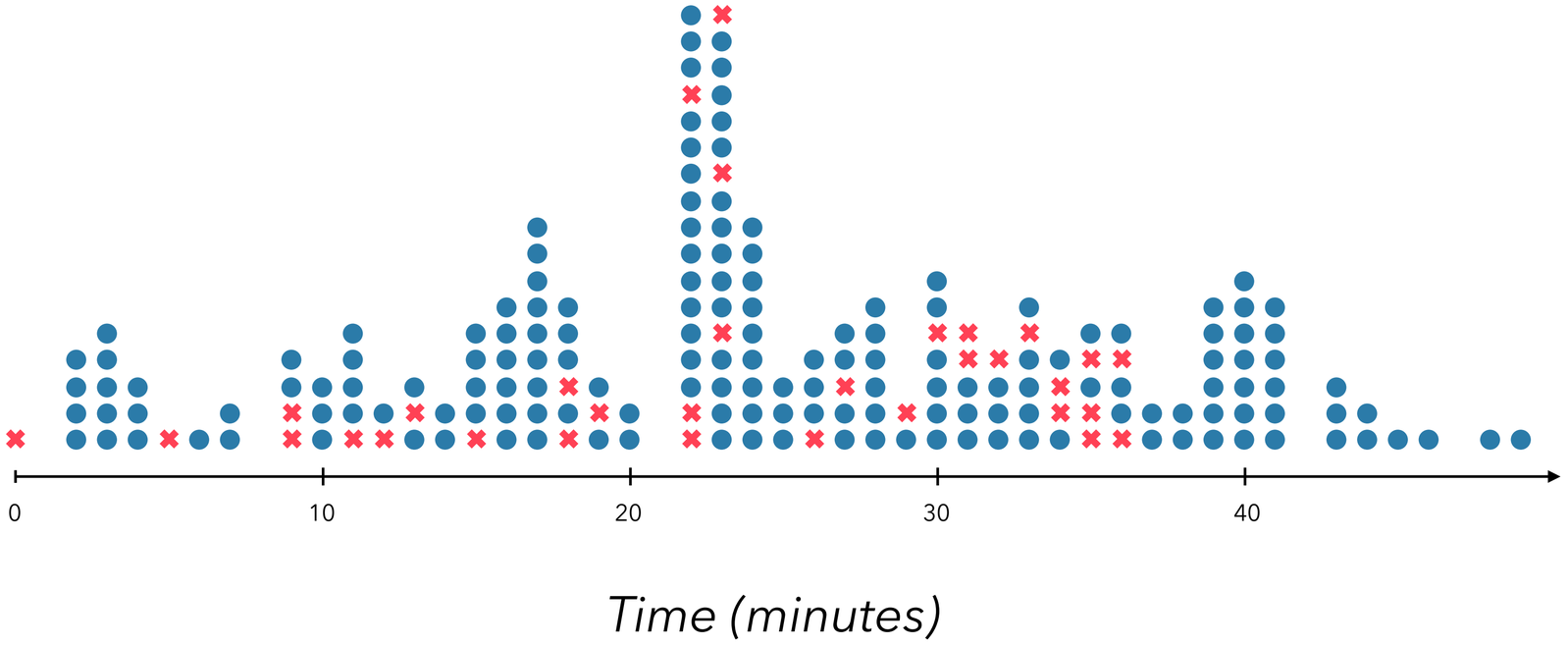
Clusters Helped Teachers Give Feedback

Participants reported that the interfaces "gave me insight into student mistakes and misconceptions" (μ = 6.2, σ = 0.44, range =1-7).

Seeing all of the similar instances of the same (or nearly the same) misconception was very useful, because it suggested ways to address common issues shared by many students.

- Participant 3, about MistakeBrowser

FixPropagator propagates fixes from dozens of corrections to hundreds of submissions.



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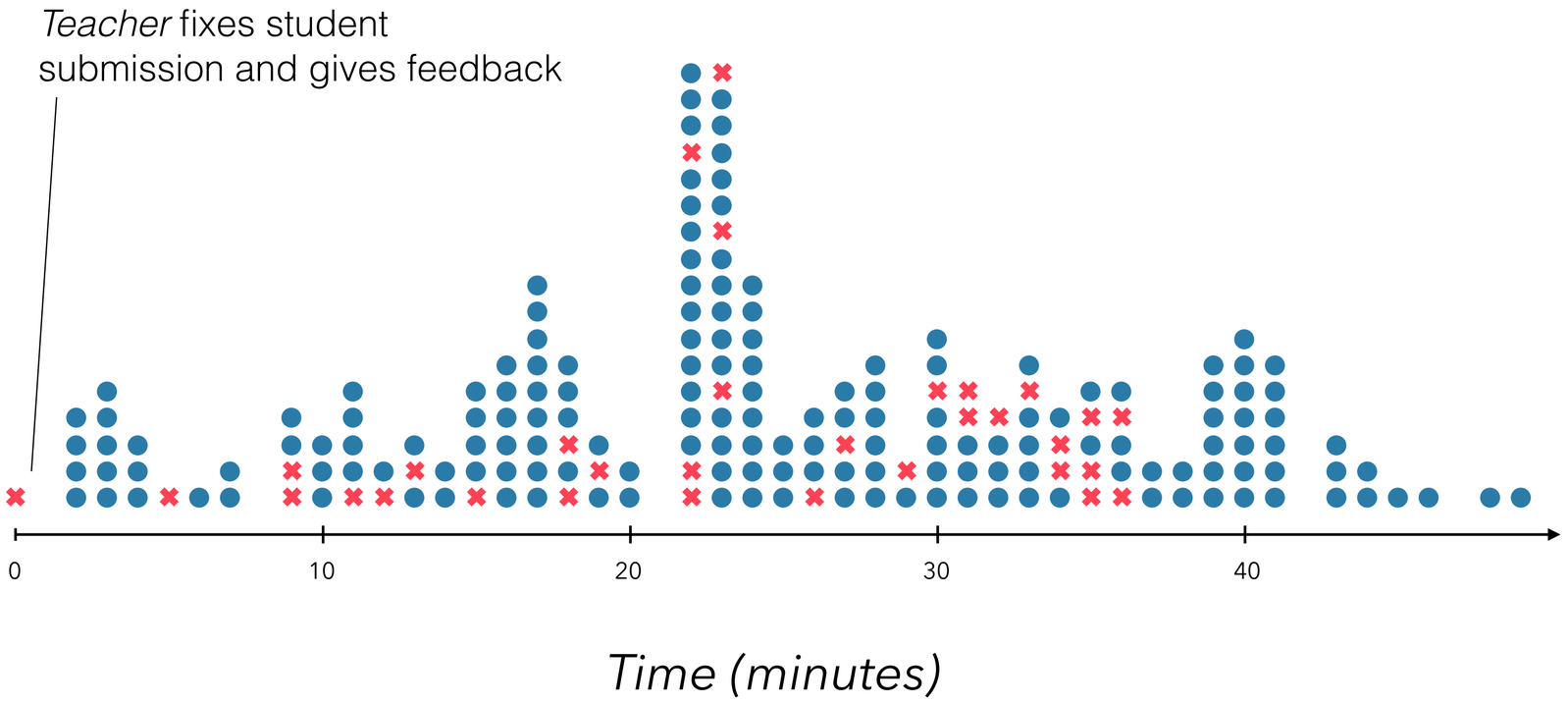

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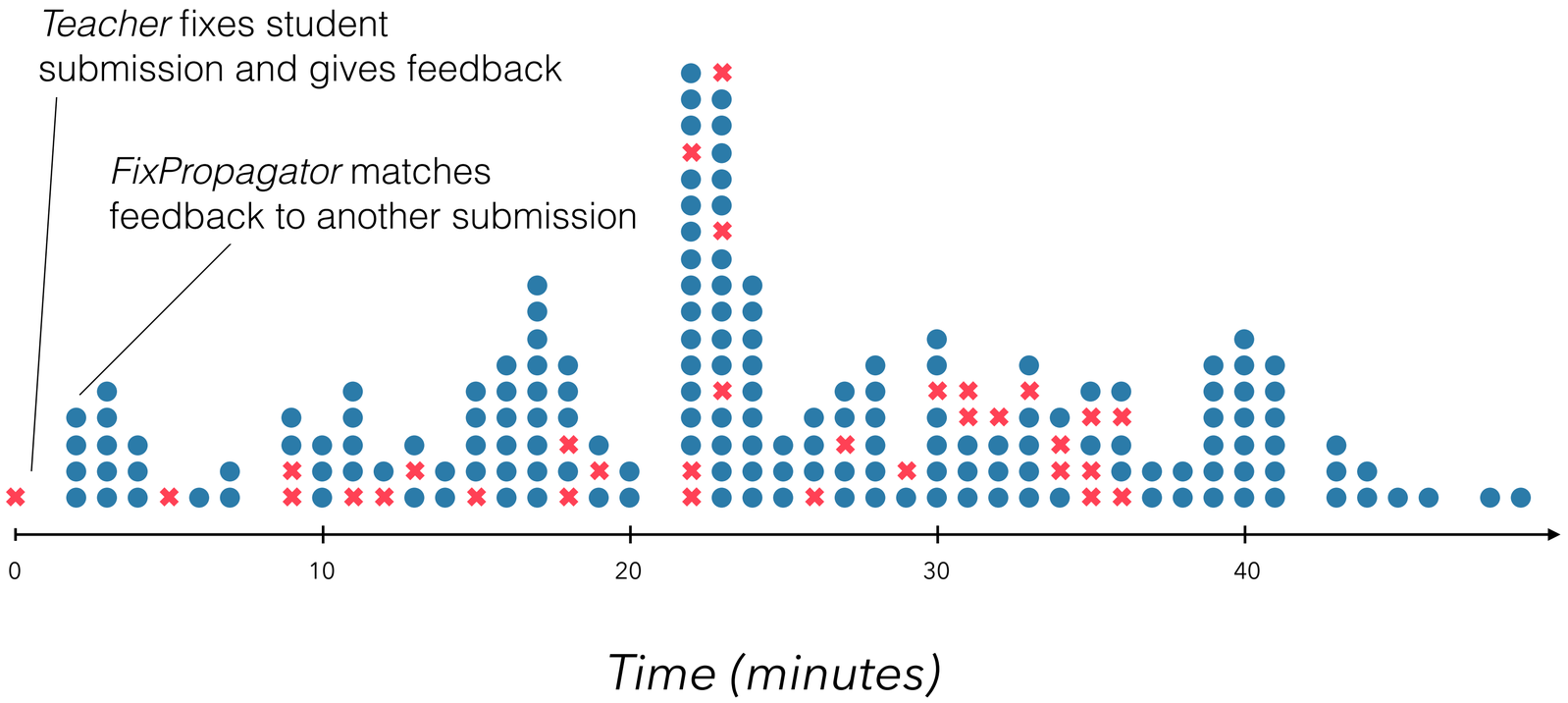

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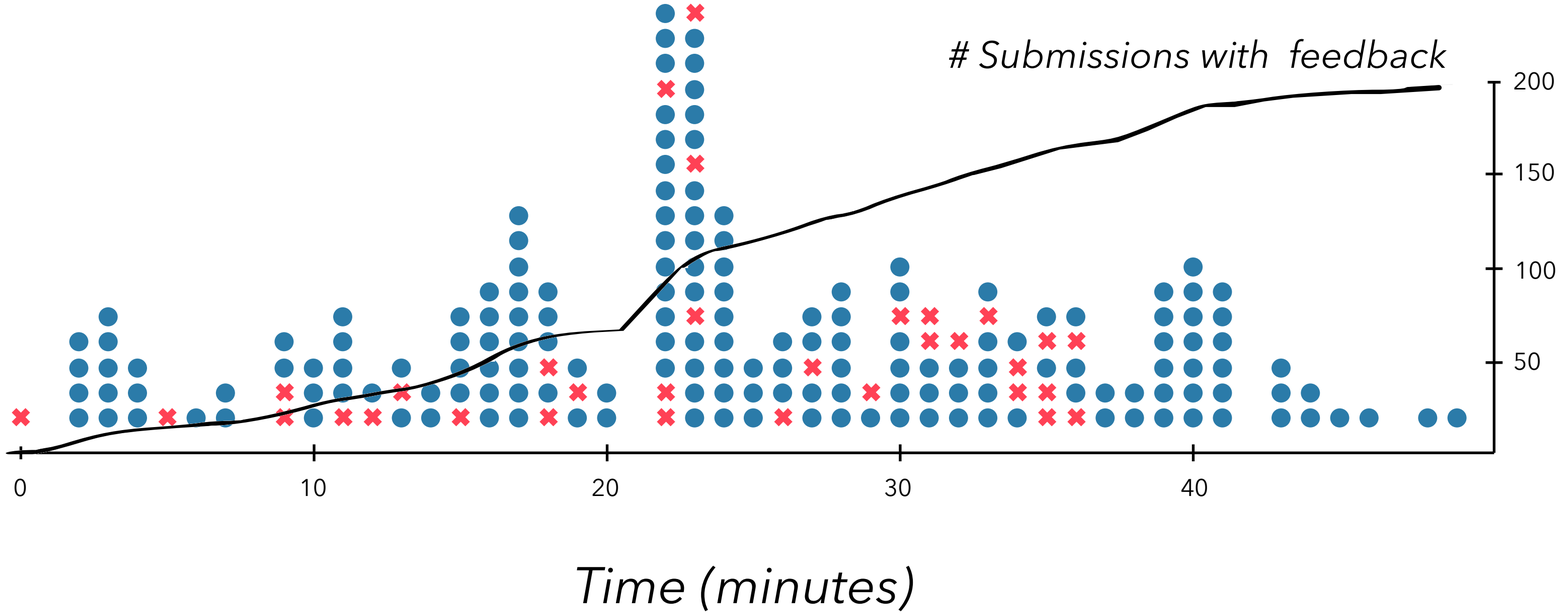

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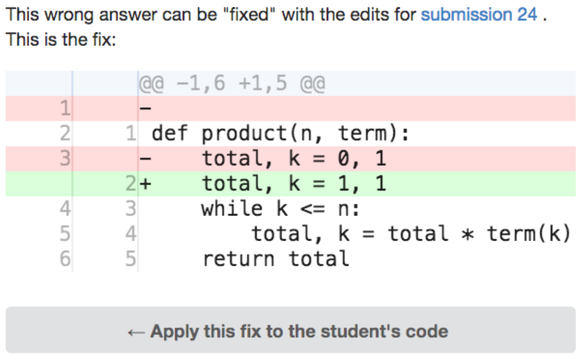

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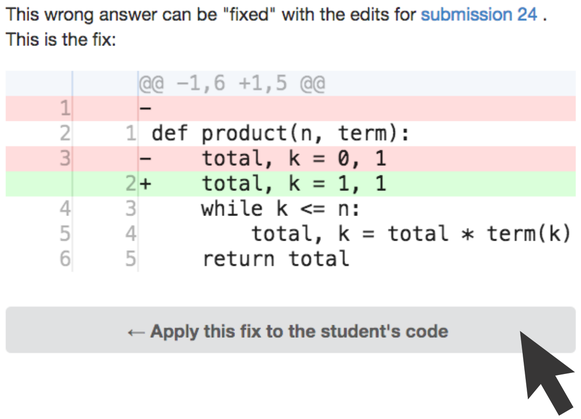

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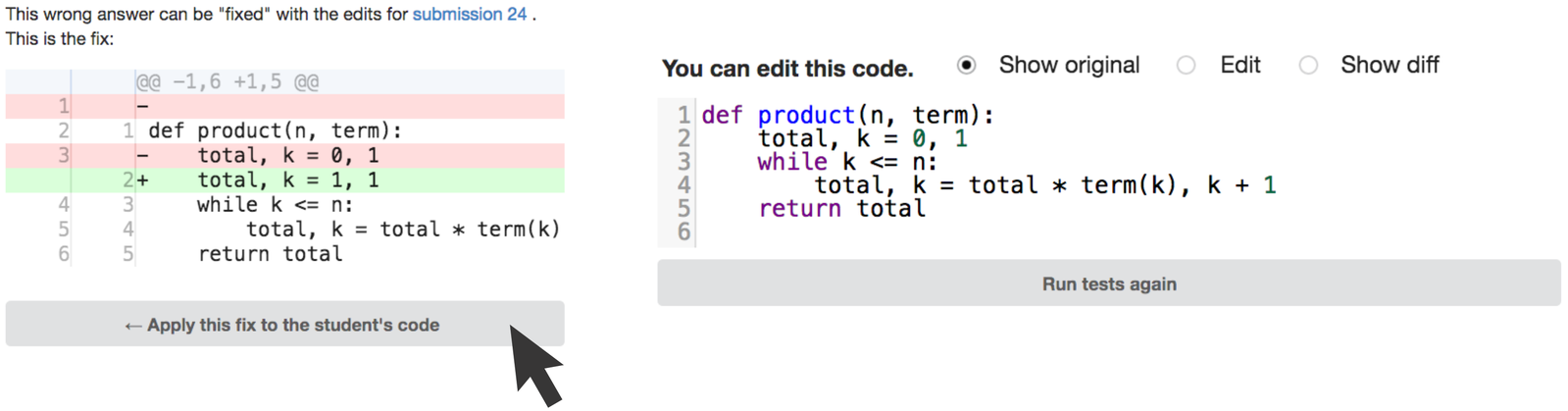

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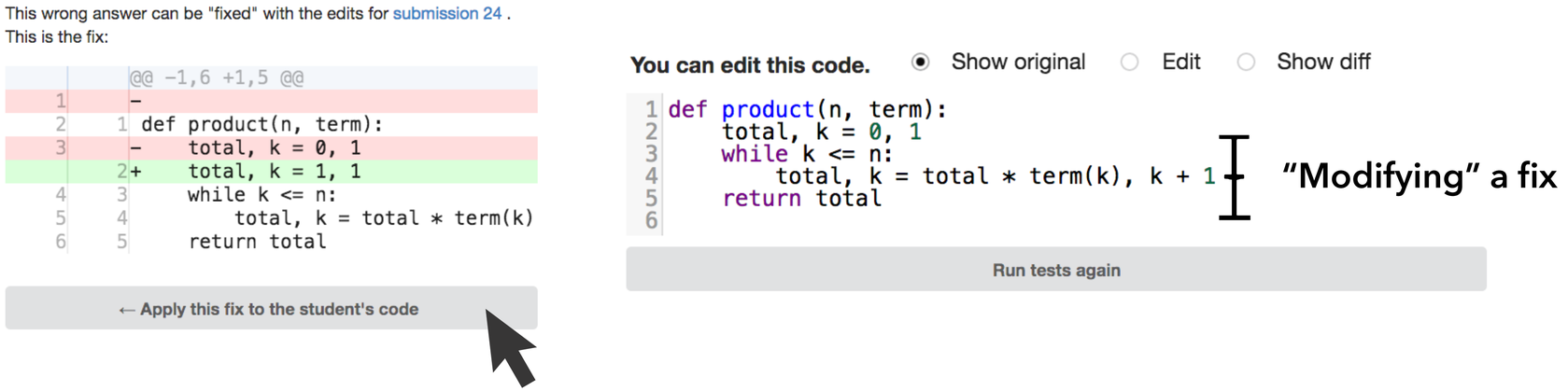

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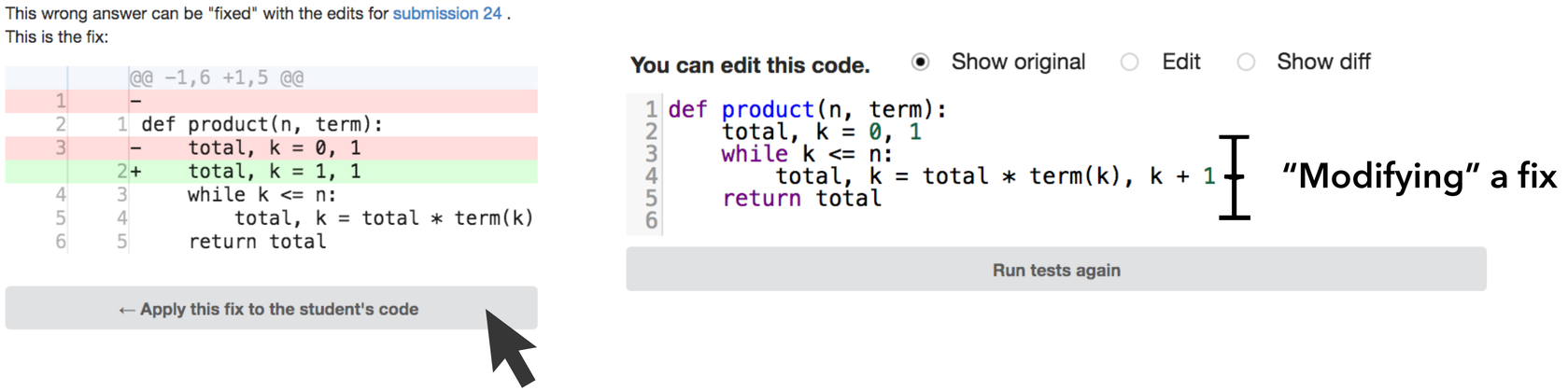

Teachers applied a median of 20 fixes, and only modified those fixes a median of 3 times.

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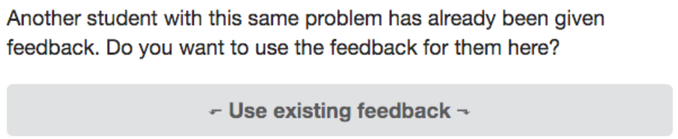

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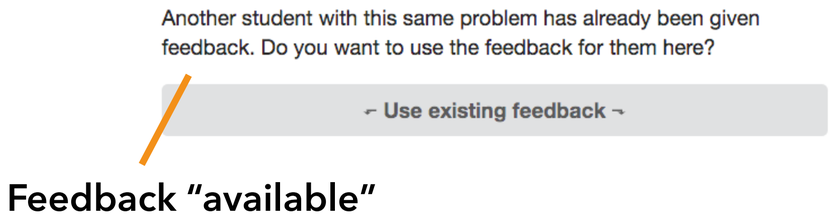

Feedback "available"

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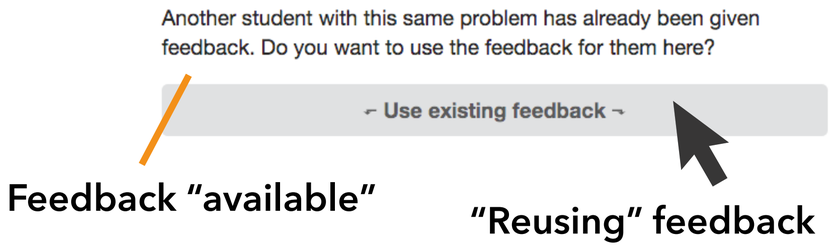

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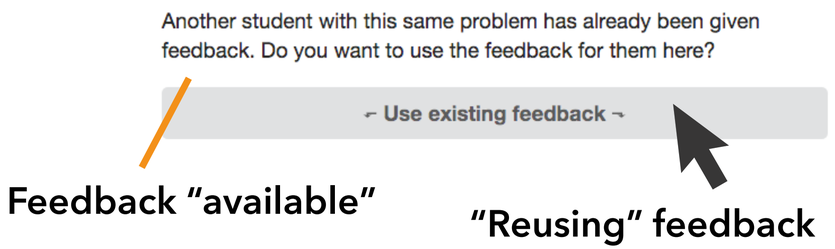

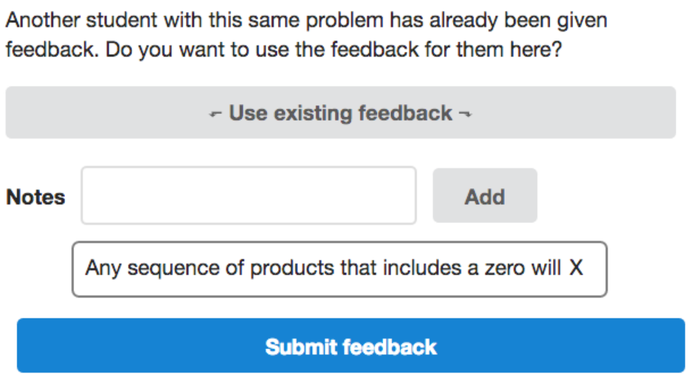

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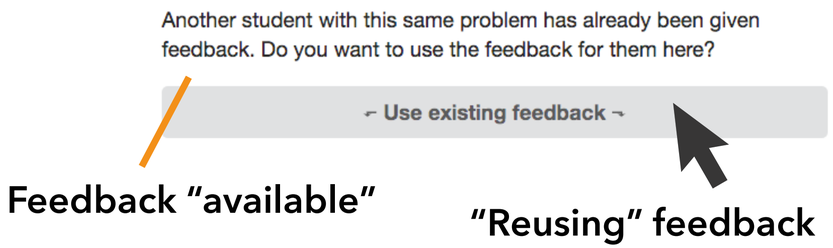

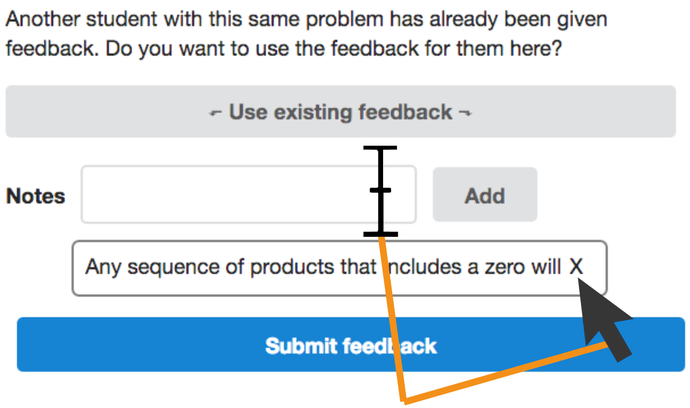

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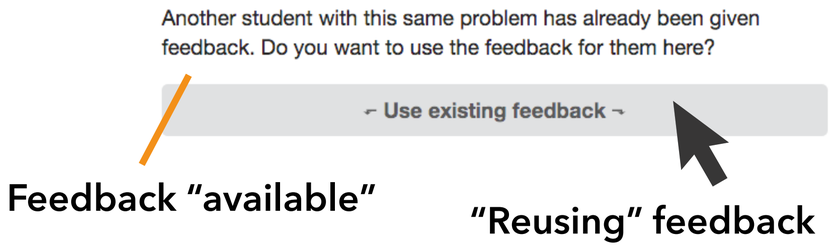

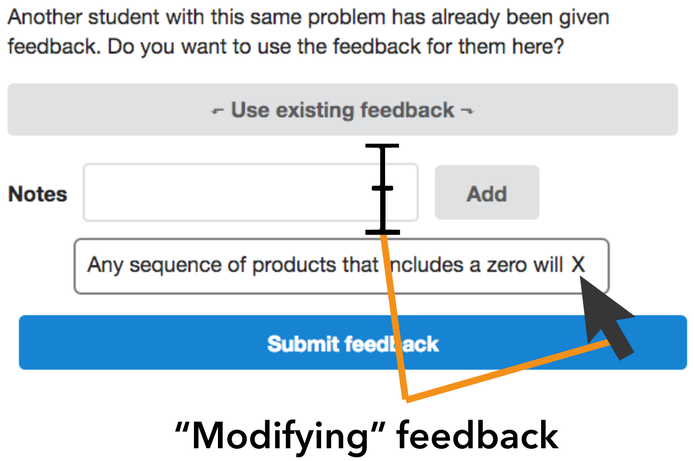

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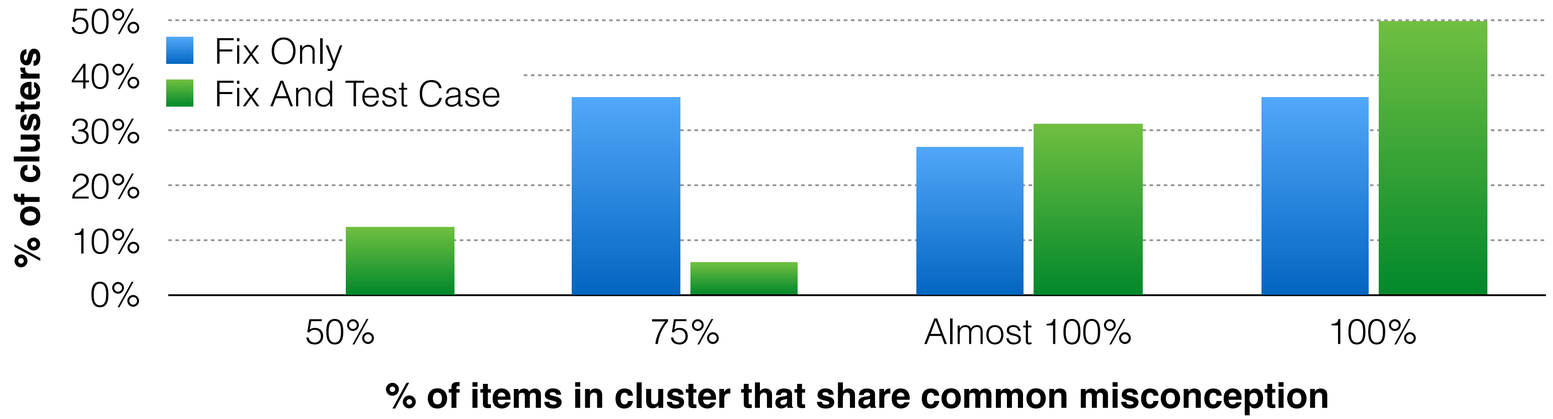
Teachers provided one piece of feedback on clusters that were mostly internally consistent.



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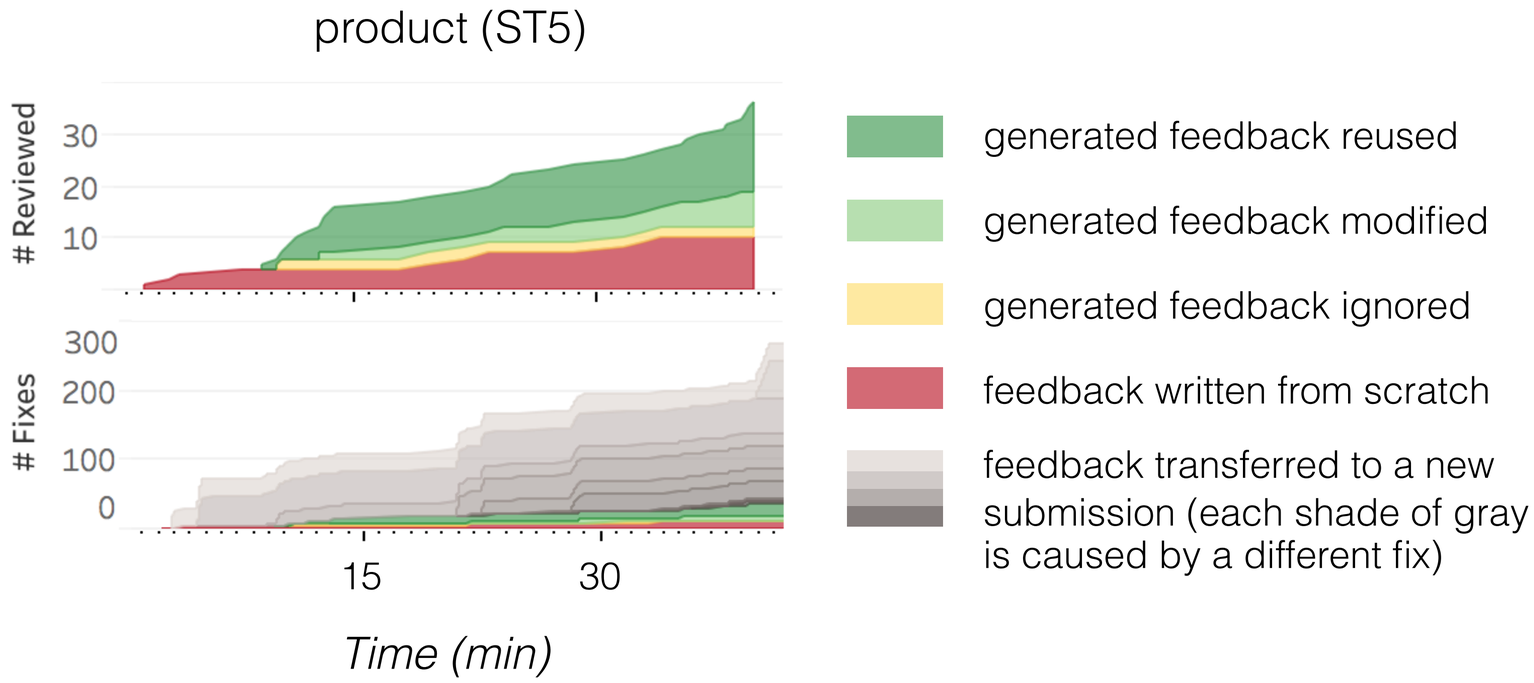


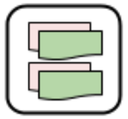
Limitations

- The impact of teacher feedback on student learning outcomes has not been evaluated
- Code transformations were created that fix submissions one or two bugs away from correct

Conclusion

We present an approach for combining human expertise with program synthesis for delivering reusable, scalable code feedback.

And two systems implementing this approach:

 MistakeBrowser

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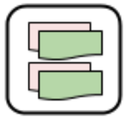 MistakeBrowser  FixPropagator

Questions?