MENTOR: Fixing Introductory Programming Assignments With Formula-Based Fault Localization and LLM-Driven Program Repair

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INESC-ID Best PhD Student 2025 Award Ceremony
Lisbon, 19 December 2025

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Motivation

- The increasing demand for programming education has given rise to all kinds of online evaluations focused on introductory programming assignments (IPAs):

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  - MIT's MOOC, Introduction to CS, **reached 1.2 M enrollments** in 2018;
  - In 2020, Stanford's CS MOOC had **more than 10K students**.

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- Providing feedback in IPAs **requires substantial time and effort by faculty**.

Automated Program Repair (APR)

Given a buggy program P_o and a set of input-output examples T (test suite).

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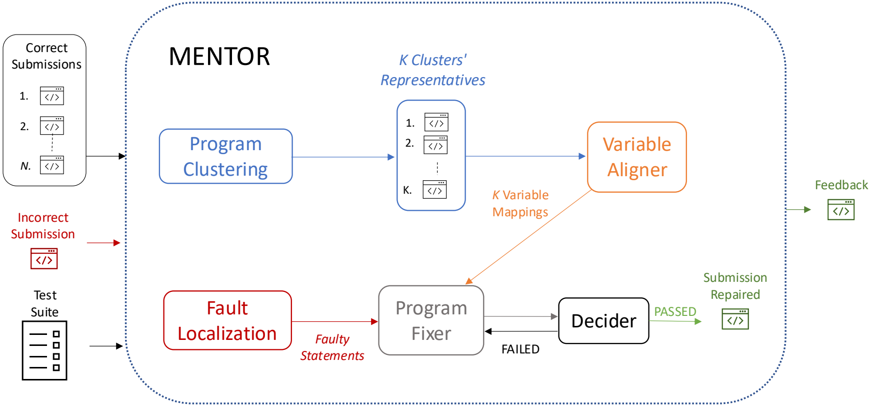
The goal of *Automated Program Repair* is to find a program P_f by **semantically change a subset S_1 of P_o's statements** ($S_1 \subseteq P_o$) for another set of statements S_2, s.t.,

$$P_f = ((P_o \setminus S_1) \cup S_2)$$

and

$$\forall (t_{in}^i, t_{out}^i) \in T \ : \ P_f(t_{in}^i) = t_{out}^i$$

MENTOR: Automated Feedback for Introductory Programming Exercises



- P. Orvalho, M. Janota, and V. Manquinho. MENTOR: Fixing Introductory Programming Assignments with Formula-Based Fault Localization and LLM-Driven Program Repair. In **JSS 2026**.

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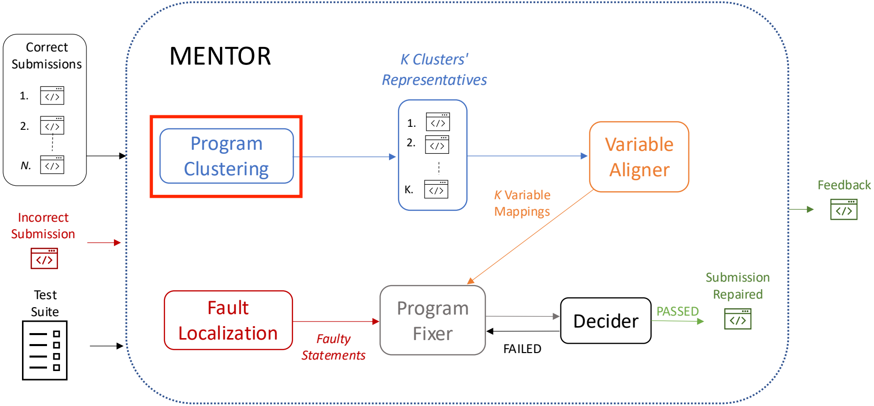

- P. Orvalho, M. Janota, and V. Manquinho. InvAASTCluster: On Applying Invariant-Based Program Clustering to Introductory Programming Assignments. In **JSS 2025**.

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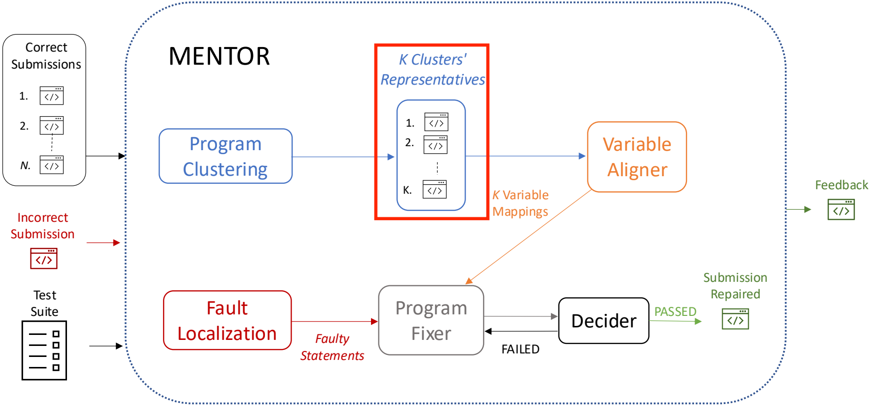

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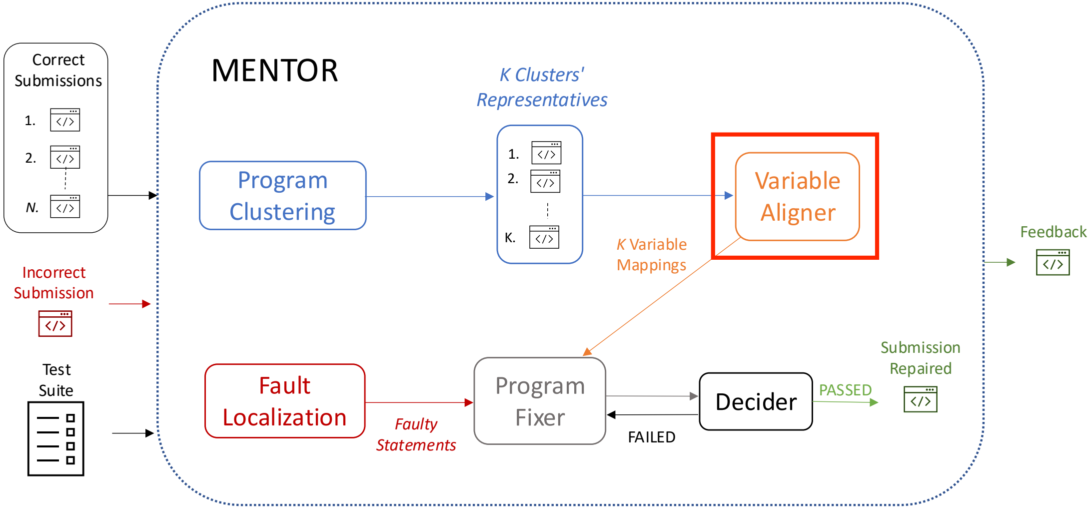

Correct Submissions
1.
2.
N.
Incorrect Submission
Test Suite
MENTOR
K Clusters' Representatives
Program Clustering
1.
2.
K.
Variable Aligner
K Variable Mappings
Fault Localization
Faulty Statements
Program Fixer
Decider
FAILED
PASSED
Submission Repaired
Feedback

Variable Mapping

- P. Orvalho, J. Piepenbrock, M. Janota, and V. Manquinho. Graph Neural Networks For Mapping Variables Between Programs. In **ECAI 2023**.
- P. Orvalho, M. Janota, and V. Manquinho. MultIPAs: Applying Program Transformations to Introductory Programming Assignments for Data Augmentation. In **ESEC/FSE 2022**.

Variable Mapping - Motivation

1: Function that finds and returns the maximum number among `n1`, `n2` and `n3`.

```
int max(int n1, int n2, int n3)
{
    int m = n1 > n2 ? n1 : n2;
    return n3 > m ? n3 : m;
}
```

2: Function that finds and returns the maximum number among `x`, `y` and `z`.

```
int max(int x, int y, int z){
    int m = 0;
    m = x > m ? x : m;
    m = y > m ? y : m;
    return z > m ? z : m;
}
```

Variable Mapping: $\{\mathtt{m} : \mathtt{m}; \mathtt{n1} : \mathtt{x}; \mathtt{n2} : \mathtt{y}; \mathtt{n3} : \mathtt{z}\}$.

Program Representation

3: An expression that uses int variables `a` and `b`, previously declared in the program.

```
1  {
2      // a and b are ints
3      a = a - b;
4  }
```

Types of edges:

AST

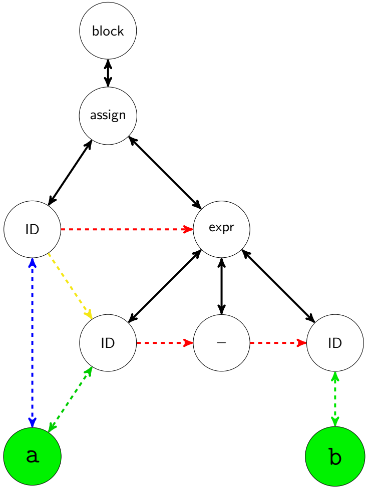
Read

Write

Sibling

Chronological

Variable Node



(a) Our program representation.

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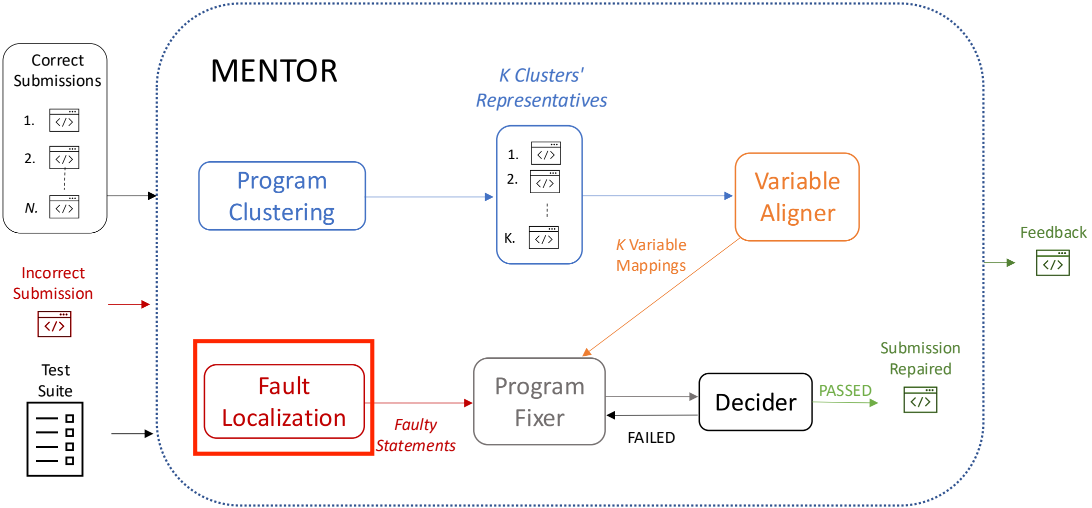

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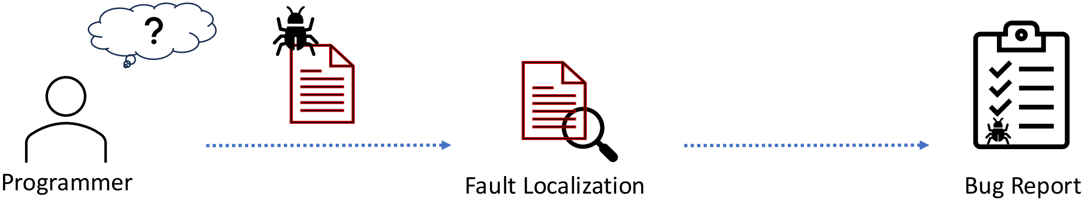
Fault Localization

- P. Orvalho, M. Janota, and V. Manquinho. CFaults: Model-Based Diagnosis for Fault Localization in C with Multiple Test Cases. In **FM 2024**.

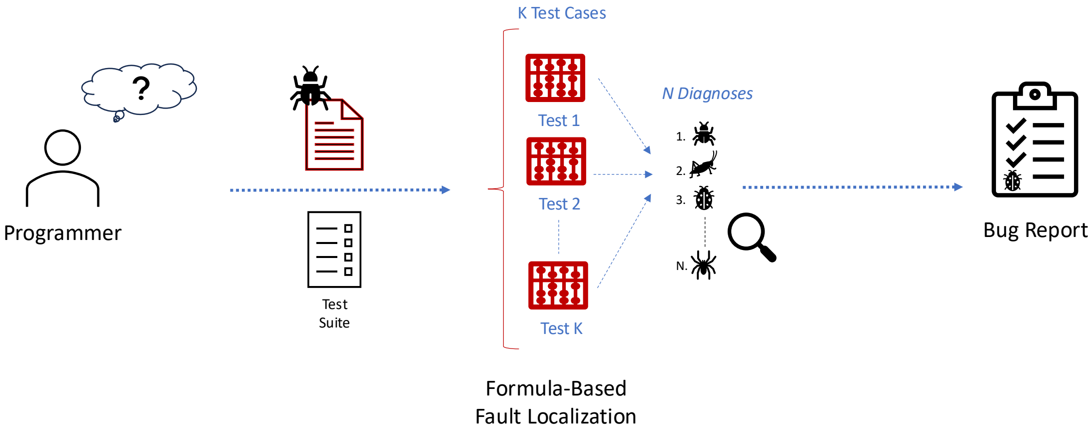
Fault Localization

- Given a buggy program, *fault localization (FL)* involves identifying locations in the program that could cause a faulty behaviour (bug).



Formula-Based Fault Localization (FBFL)

- FBFL methods encode the localization problem into **several optimization problems** to identify a minimal set of bugs (diagnoses).



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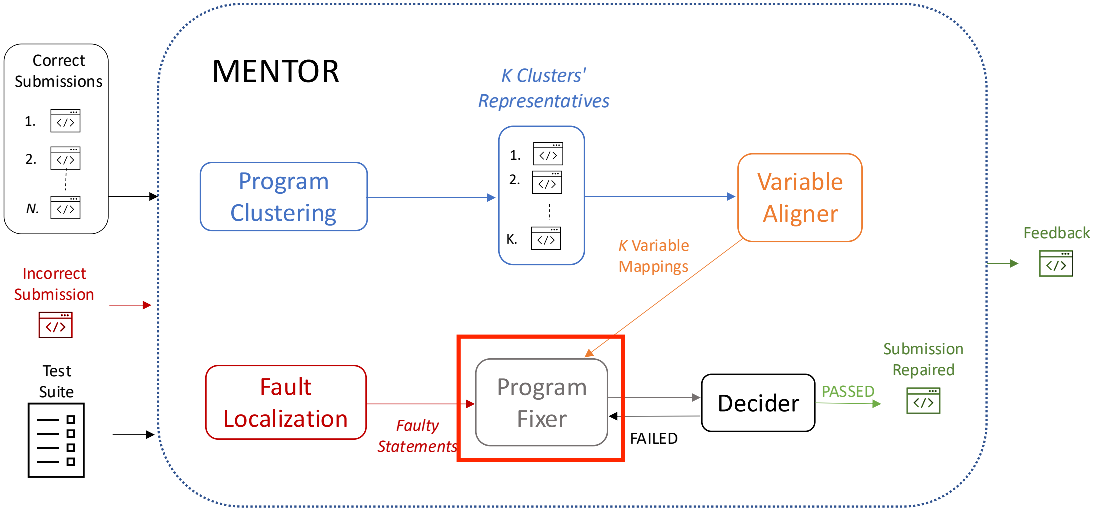
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Program Repair

- P. Orvalho, M. Janota, and V. Manquinho. Counterexample Guided Program Repair Using Zero-Shot Learning and MaxSAT-based Fault Localization. In **AAAI 2025**.

Motivation

4: Semantically incorrect program. Faults: {4,8}.

```c
1  int main(){ //finds max of 3 nums
2      int f,s,t;
3      scanf("%d%d%d",&f,&s,&t);
4      if (f < s && f >= t)
5          printf("%d",f);
6      else if (s > f && s >= t)
7          printf("%d",s);
8      else if (t < f && t < s)
9          printf("%d",t);
10
11     return 0;
12 }
```

Motivation

5: Semantically incorrect program. Faults: {4,8}.

```
1  int main(){ //finds max of 3 nums
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6: Semantically incorrect program. Faults: {4,8}.

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LLMs for code (LLMCs)

- GRANITE and CODEGEMMA **cannot fix** the buggy program within 90 secs;

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7: Semantically incorrect program. Faults: {4,8}.

```
1   int main(){ //finds max of 3 nums
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LLMs for code (LLMCs)

- Granite and CodeGemma **cannot fix** the buggy program within 90 secs;
- Even if we provide the assignment's **description and IO tests**.

Program Sketches

8: Semantically incorrect program. Faults :{4,8}.

```
1  int main(){ //finds max of 3 nums
2      int f,s,t;
3      scanf("%d%d%d",&f,&s,&t);
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7          printf("%d",s);
8      else if (t < f && t < s)
9          printf("%d",t);
10
11     return 0;
12 }
```
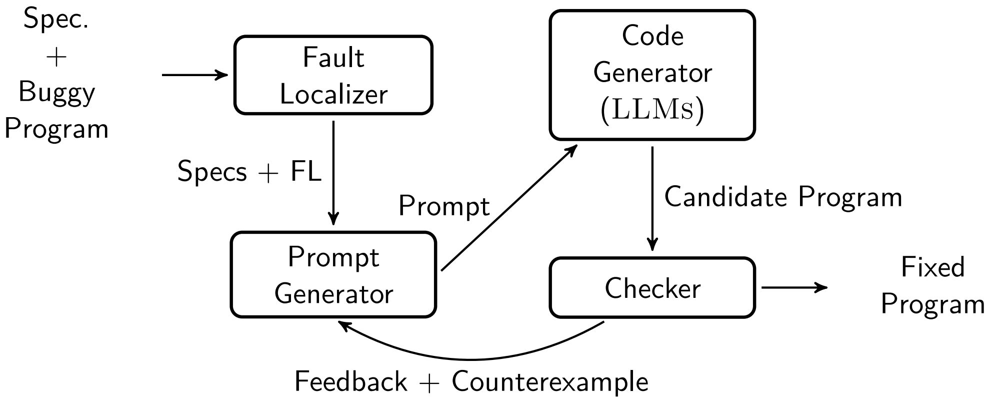

9: Program sketch with holes.

```
1  int main(){
2      int f,s,t;
3      scanf("%d%d%d",&f,&s,&t);
4      @ HOLE 1 @
5          printf("%d",f);
6      else if (s > f && s >= t)
7          printf("%d",s);
8      @ HOLE 2 @
9          printf("%d",t);
10
11     return 0;
12 }
```

Counterexample Guided Automated Repair

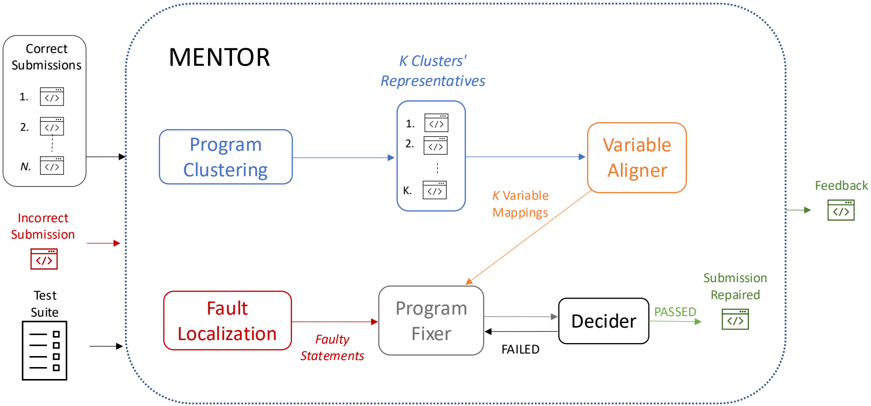


LLM-Driven APR with CFaults

	Prompt Configurations			
LLMs	**De-TS**	**De-TS-CE**	**Sk_De-TS**	**Sk_De-TS-CE**
CodeGemma	41.7%	42.3%	47.7%	**48.1%**
CodeLlama	34.4%	34.9%	**40.0%**	39.2%
Gemma	34.7%	34.4%	37.2%	**37.3%**
Granite	43.7%	43.6%	**48.3%**	47.6%
Llama3	39.4%	41.2%	40.4%	**41.3%**
Phi3	34.5%	34.2%	**38.2%**	37.4%
Verifix	6.3%			
Clara	34.6%			

Table 1: The number of programs fixed by each LLM under various configurations. Mapping abbreviations to configuration names: **De** - IPA *Description*, **TS** - *Test Suite*, **CE** - *Counterexample*, **SK** - *Sketches*.

MENTOR: Automated Feedback for Introductory Programming Exercises



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Takeaway Message

- We tackle the APR problem using an **LLM-Driven Counterexample Guided Inductive Synthesis (CEGIS) approach** [Solar-Lezama et al., 2006];

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Takeaway Message

- We tackle the APR problem using an **LLM-Driven Counterexample Guided Inductive Synthesis (CEGIS) approach** [Solar-Lezama et al., 2006];

- We employ **Logic-based Fault Localization to guide and minimize LLMs' patches** to incorrect programs by feeding them bug-free program sketches;

- With our approach **all six evaluated LLMs fix more programs and produce smaller patches** than other configurations and symbolic tools;

Takeaway Message

- We tackle the APR problem using an **LLM-Driven Counterexample Guided Inductive Synthesis (CEGIS) approach** [Solar-Lezama et al., 2006];
- We employ **Logic-based Fault Localization to guide and minimize LLMs' patches** to incorrect programs by feeding them bug-free program sketches;
- With our approach **all six evaluated LLMs fix more programs and produce smaller patches** than other configurations and symbolic tools;
- All our code is available on GitHub and on Zenodo.

Obrigado!
Thank you!

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My sincere thanks to INESC-ID,

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My sincere thanks to INESC-ID,
and to my advisors, Vasco and Mikoláš!

Pedro Orvalho

Thank you!

https://pmorvalho.github.io

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