Graph-based, Self-Supervised Program Repair from Diagnostic Feedback

ICML 2020

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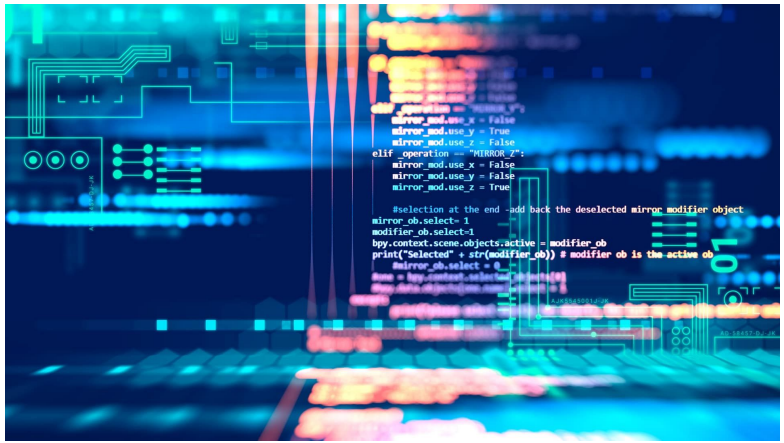
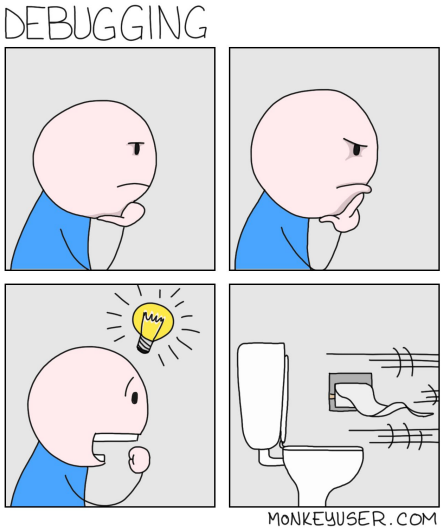
Why program repair?

Programmers spend 75% of time fixing source code errors

Automatic program repair can dramatically enhance programming productivity



Dream



Reality

Theme: Learning from Feedback

Humans learn from feedback

Write code → compile/execute → **repair code based on feedback**

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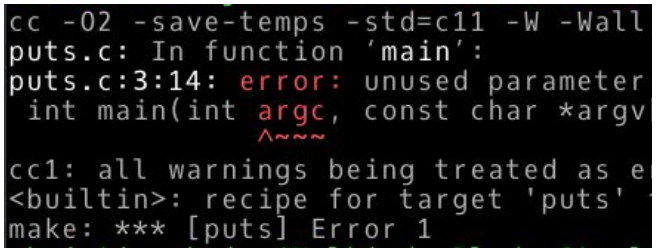
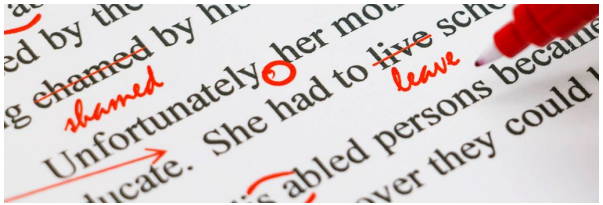
General framework with many other applications

- Edit essays based on written feedback
- Learn from user inputs in interactive dialogue



Repair programs based on errors



Edit essays based on feedback

Example

Broken program

```
 1  #include <bits/stdc++.h>
 2  #include <string>
 3  using namespace std;
 4  int main() {
 5    char tmp,  a , b;
 6    map<string,int> mp;
 7    cin >>  a  >> b;
 8    int i, j;
 9    for (i = 0; i <  a .size(); i++){
10      tmp.push_back( a [i]);
11      string tmp1 = tmp;
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```

Example

Should be `string`

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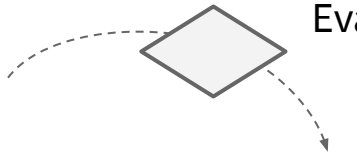

Evaluator (compiler)

Feedback

```
line 9:error: request for
member ‘size’ in ‘a’, which
is of non-class type ‘char’
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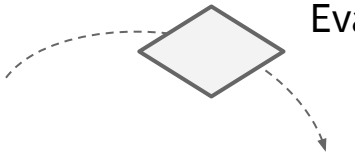

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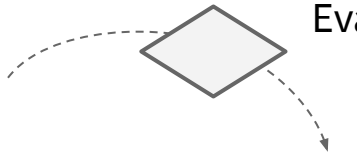

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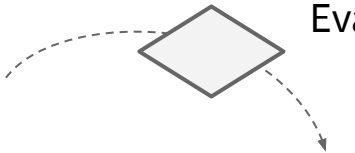

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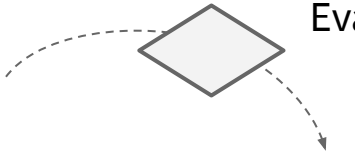

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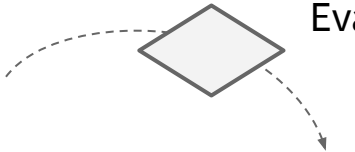

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Repair!

1. Error localized **line 5**
2. Repair

```
  char tmp, a, b;
→ string tmp, a, b;
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Goal: learn to repair programs from error messages

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Diagnostic Feedback

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DrRepair (our system)

1. Error localized **line 5**

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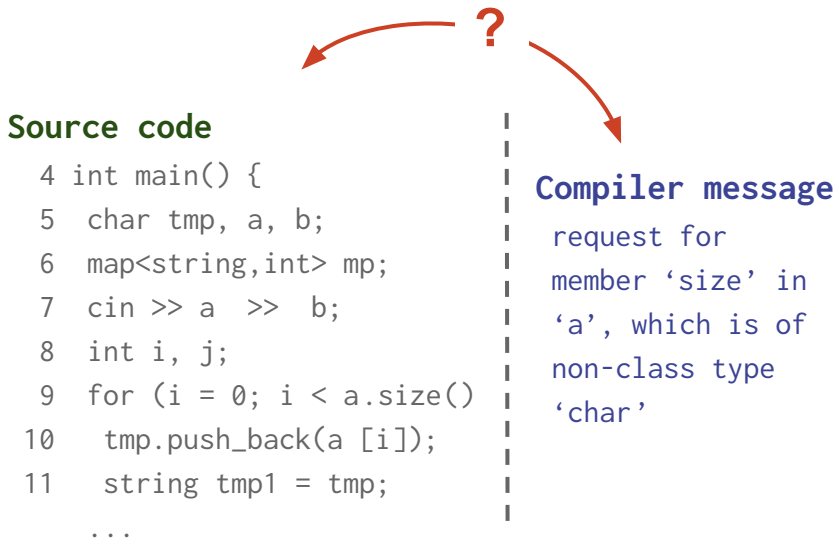
Challenges

1. **Modeling**
   - How to connect two modalities: **program** and **feedback**?
   - How to model the **reasoning** of repair (e.g. tracking symbols)?



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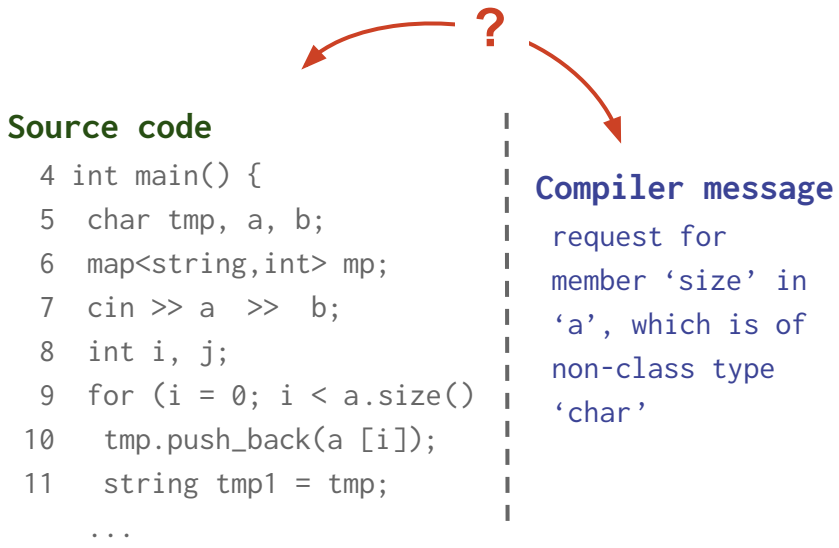
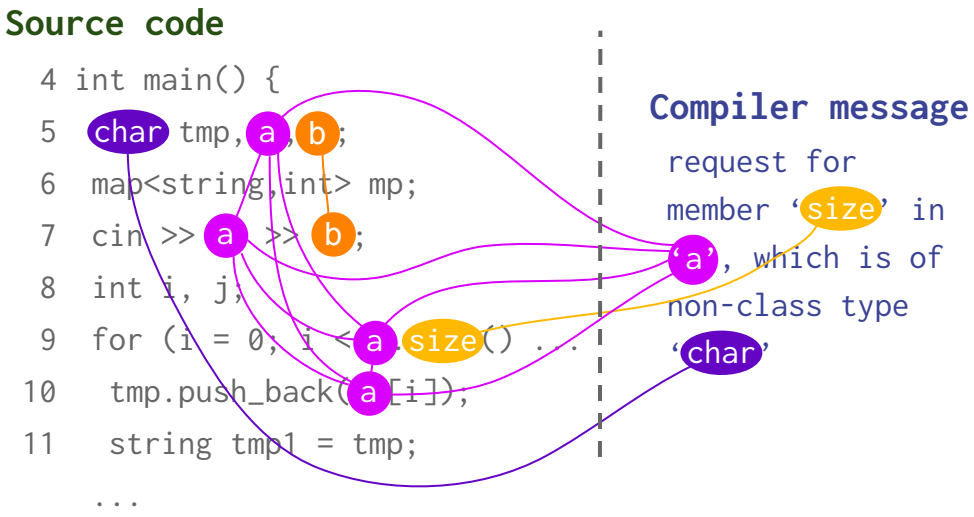


2. **Data**
   - Existing works rely on labeled datasets of <broken code, fixed code>
   - Relatively small (10–100K data points). How to **scale up**?

Our contributions

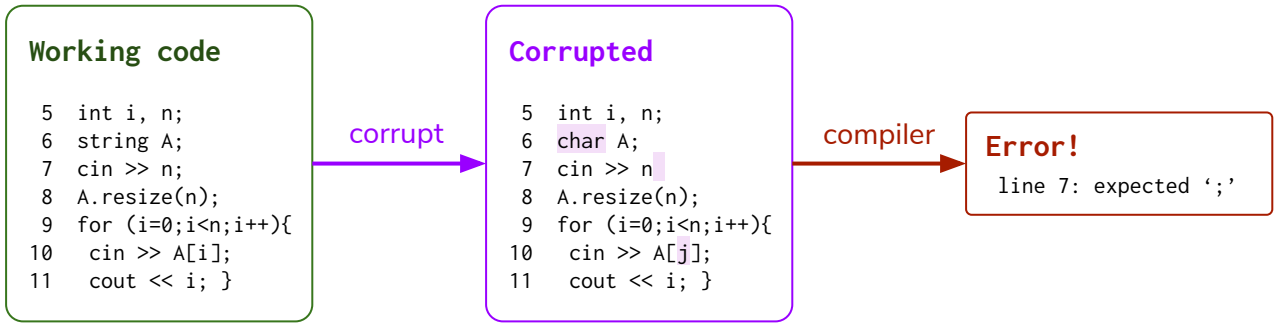
1. **Program-feedback graph**
   - Connect symbols across **program** & **feedback**
   - Performs reasoning via **graph-attention**



Our contributions

2. **Self-supervised learning**
   - Collect unlabeled programs
   - Corrupt and get diagnostic feedback (e.g. run compiler)

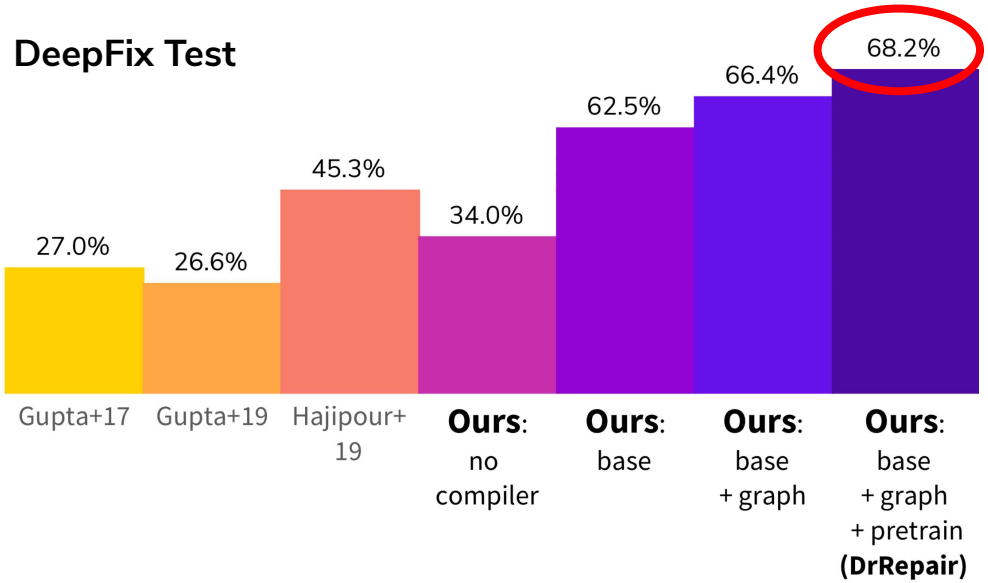
⇒ **Extra training data**: <broken code, feedback, fixed code>

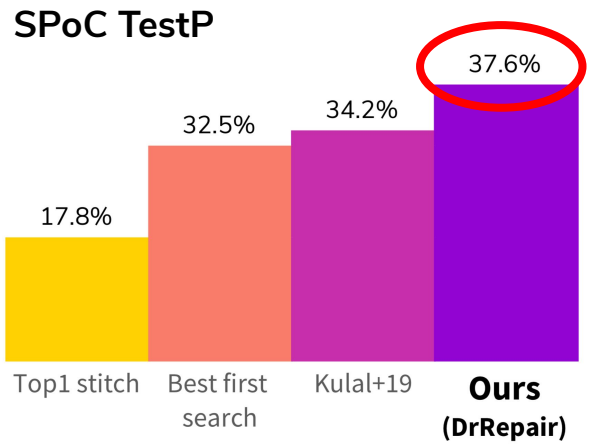


Our results

Improved performance on two applications

- DeepFix: correct intro programming assignments in C
- SPoC: correct output of C++ program synthesis





Outline

- Innovations
    1. Reasoning via program-feedback graph
    2. Self-supervised learning
- Evaluations
    1. DeepFix
    2. SPoC
- Analysis & Examples
- Takeaways

1. Reasoning via program-feedback graph

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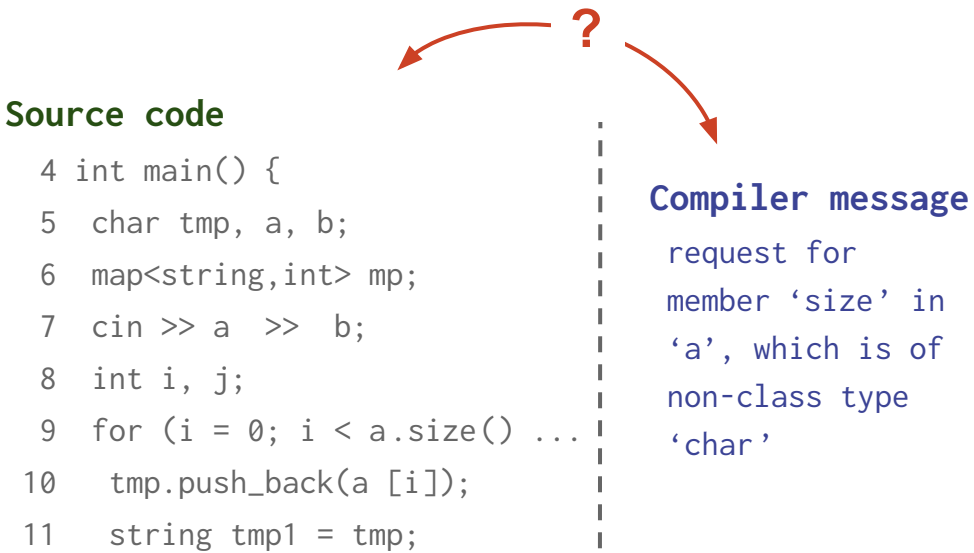
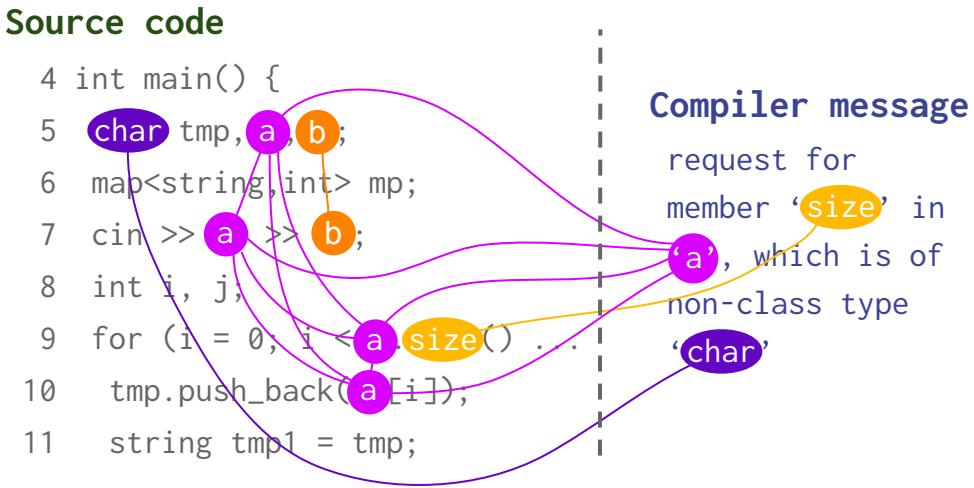


1. Reasoning via program-feedback graph

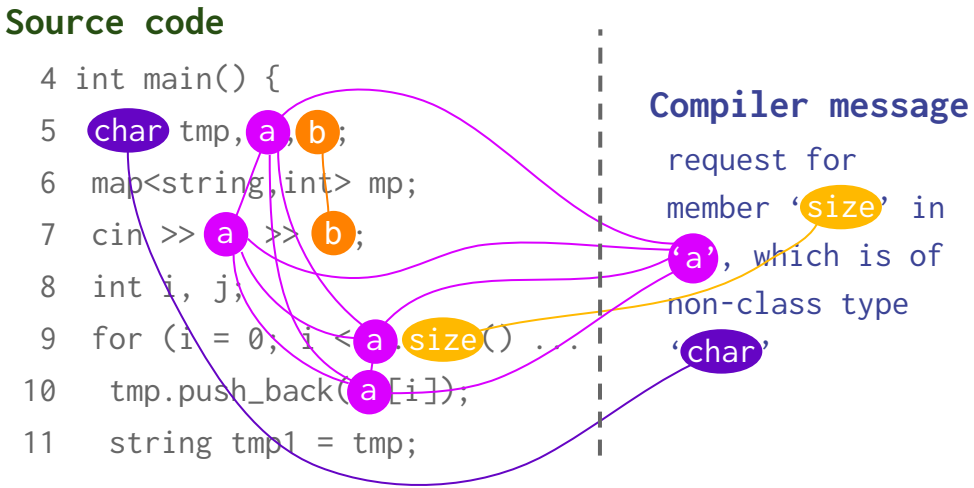
Our solution: program-feedback graph



1. Reasoning via program-feedback graph

Our solution: program-feedback graph

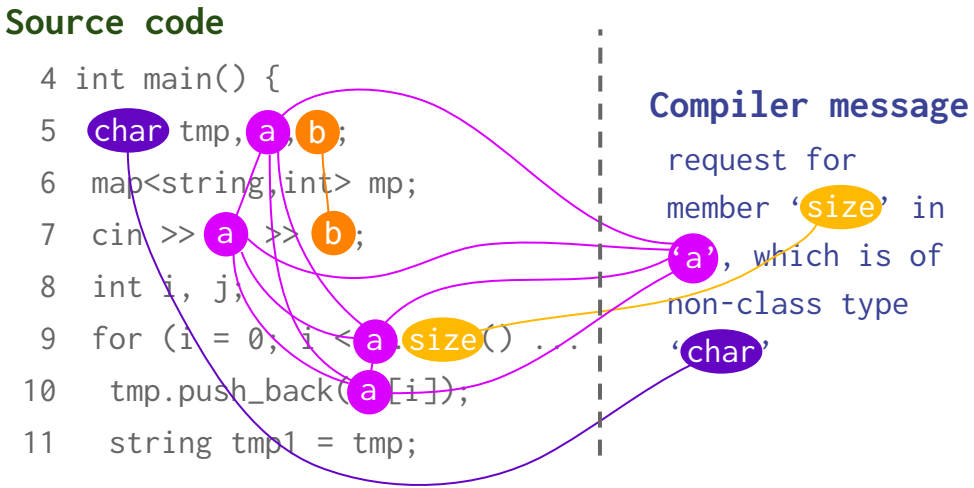
- Join program & feedback through symbols relevant to program repair
  → shared/abstracted semantic space



1. Reasoning via program-feedback graph

Our solution: program-feedback graph

- Join program & feedback through symbols relevant to program repair
  → shared/abstracted semantic space
- Reason over this space using graph attention



1. Reasoning via program-feedback graph

How to construct graph?

- Recognize token types

Source code

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Compiler message

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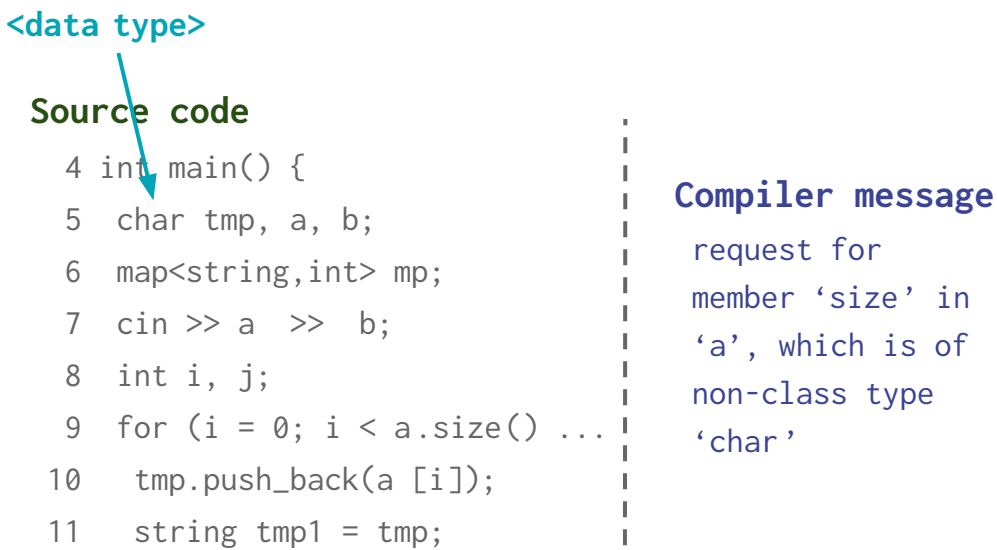

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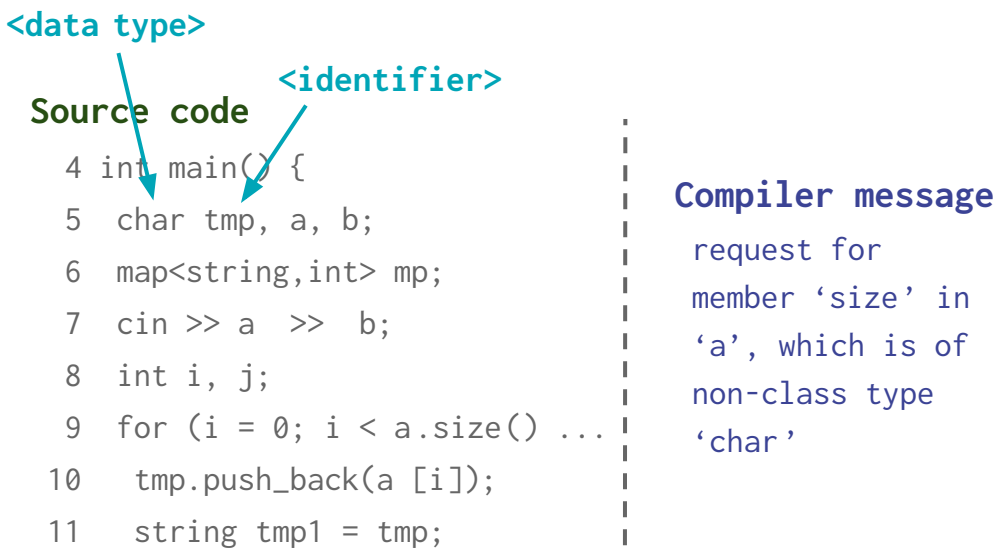

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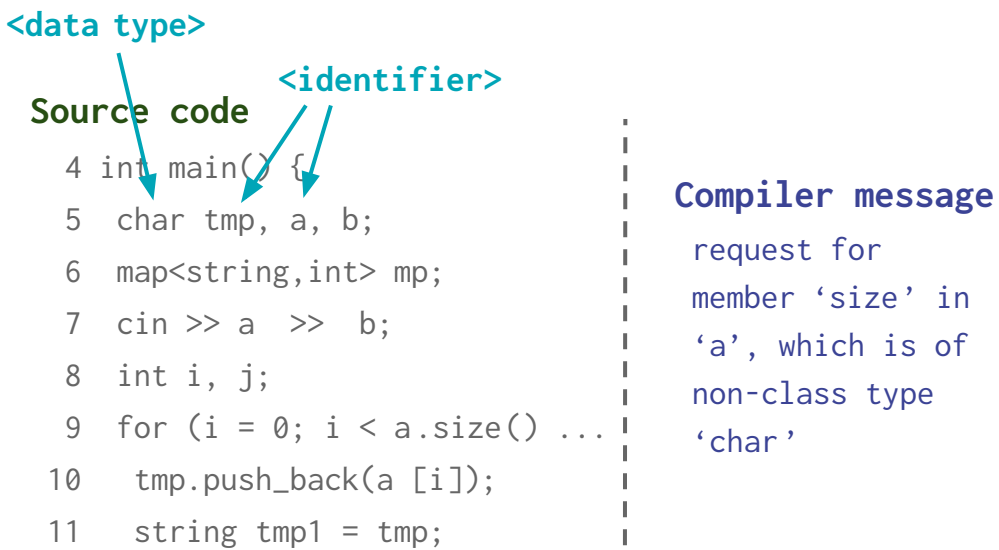

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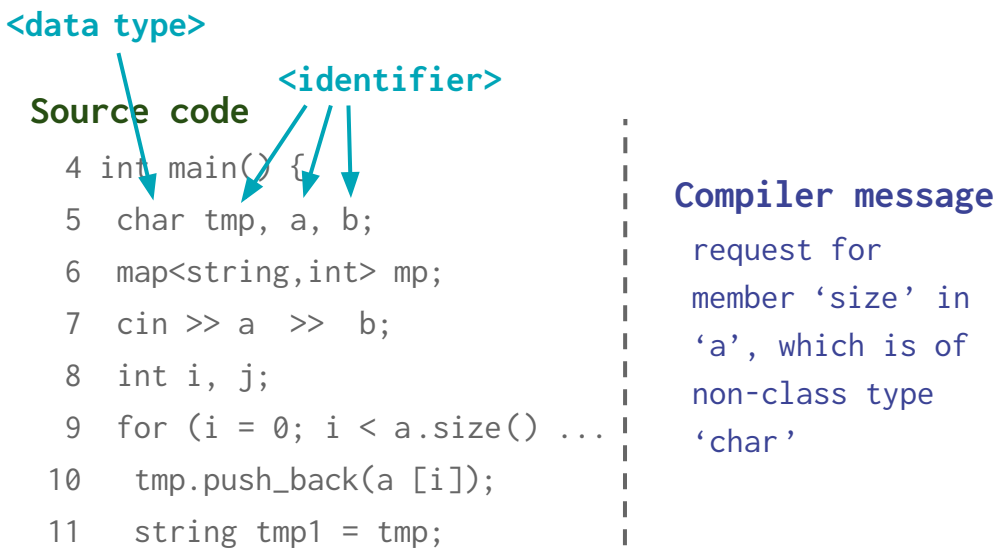

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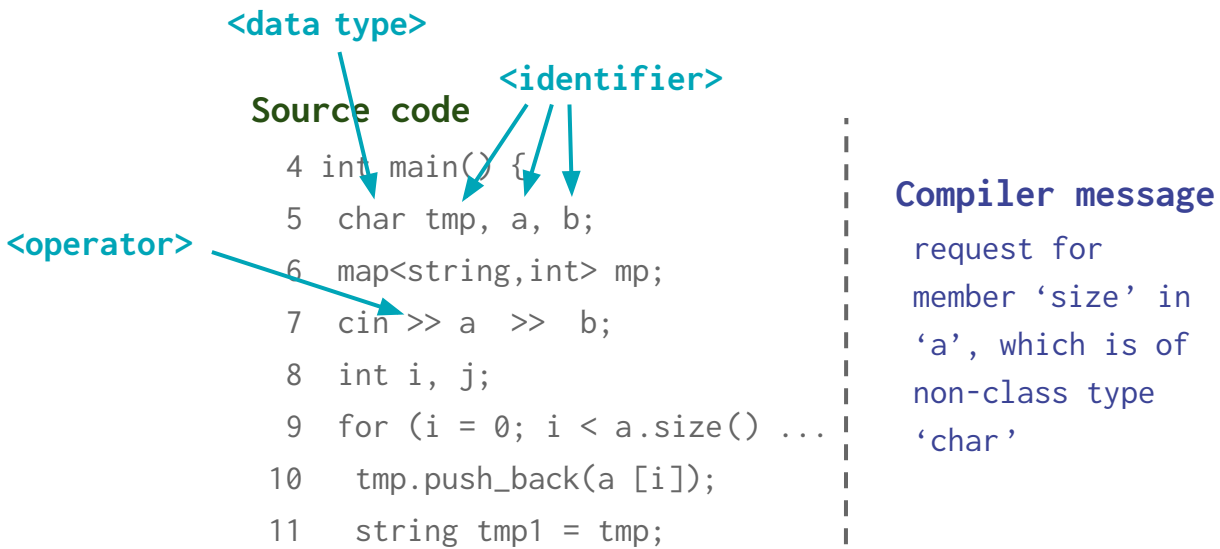

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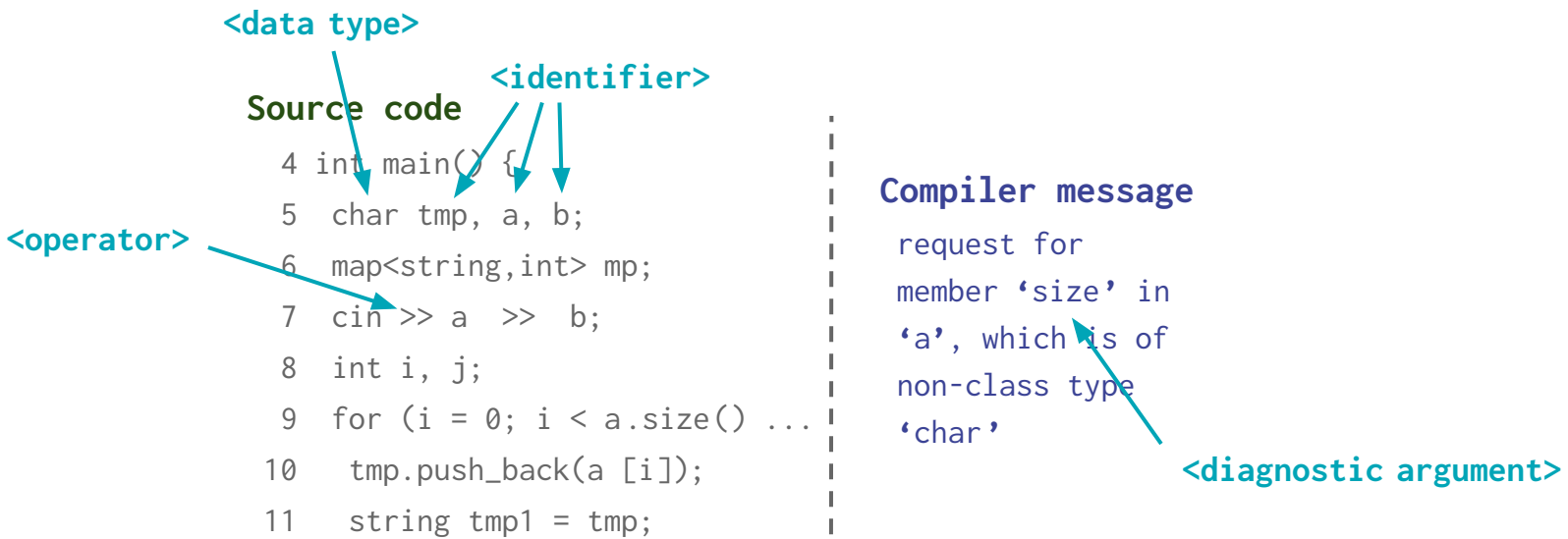

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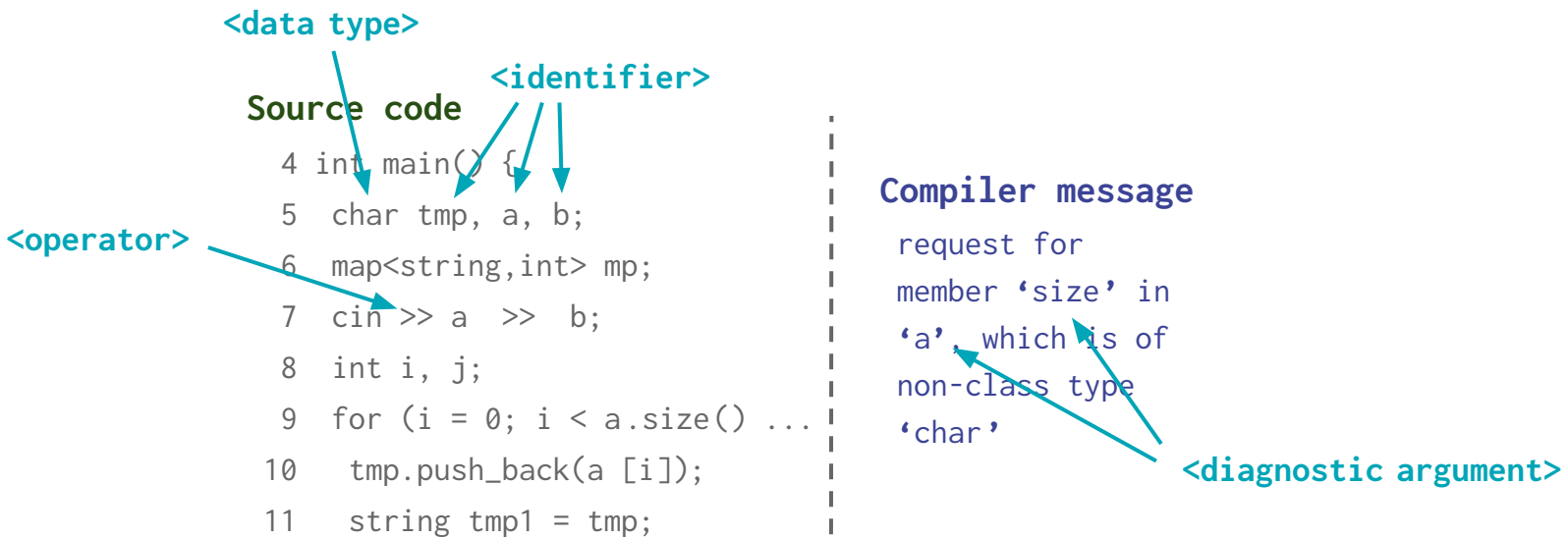

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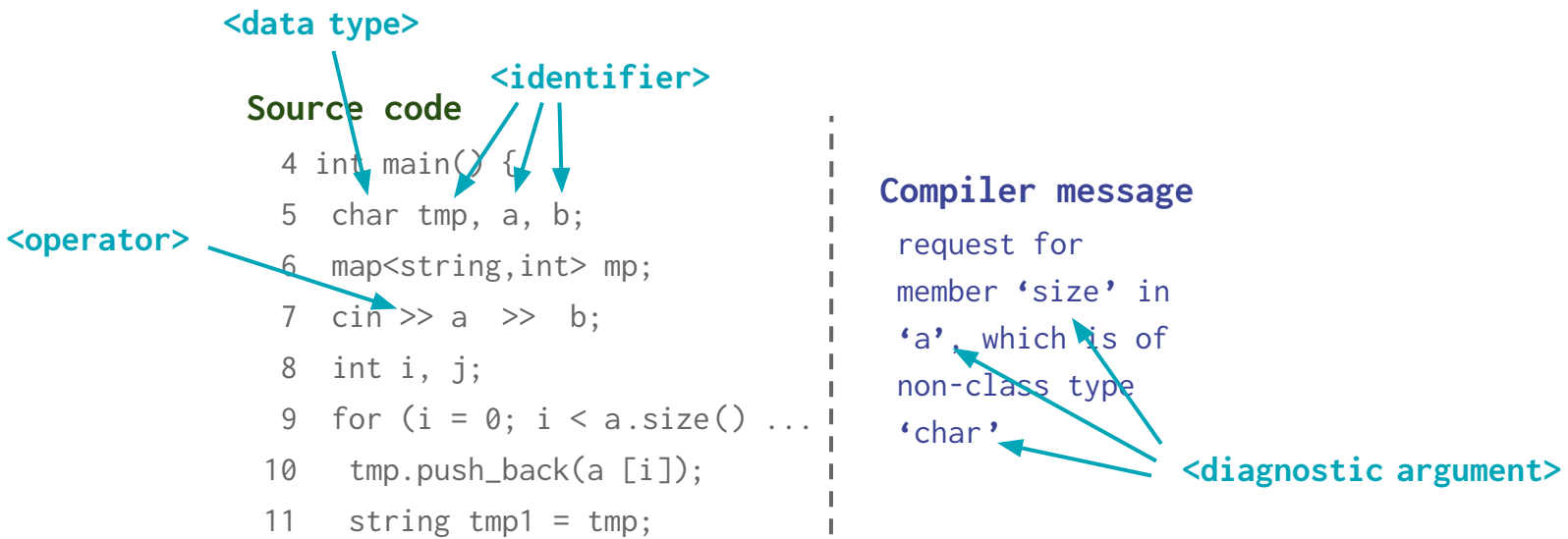
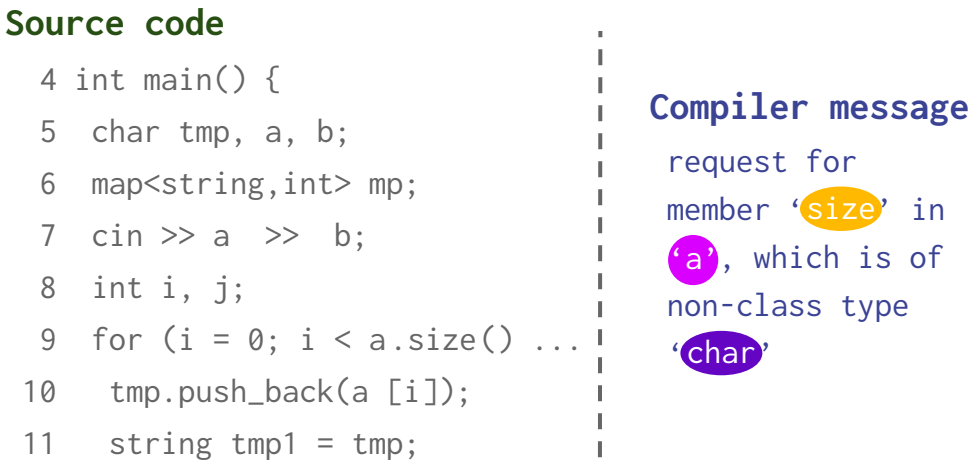


1. Reasoning via program-feedback graph

How to construct graph?

- Recognize token types
- **Nodes**: diagnostic arguments



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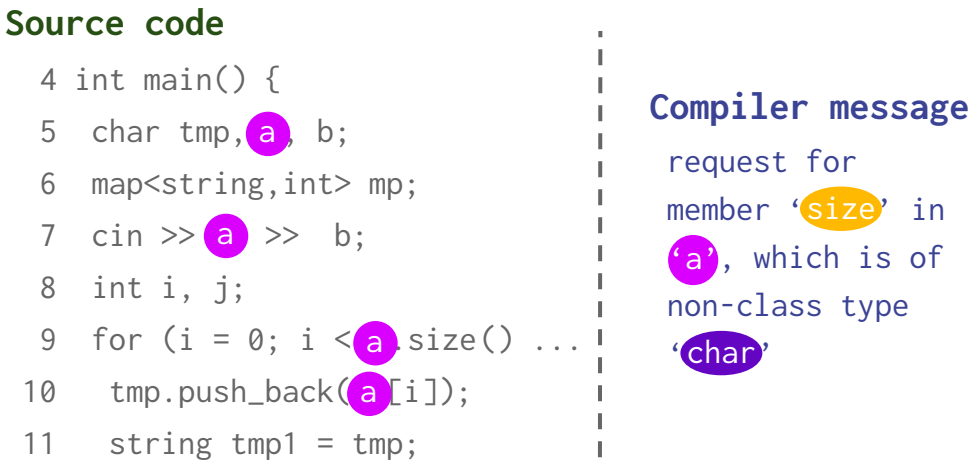
- **Nodes**: diagnostic arguments, their occurences



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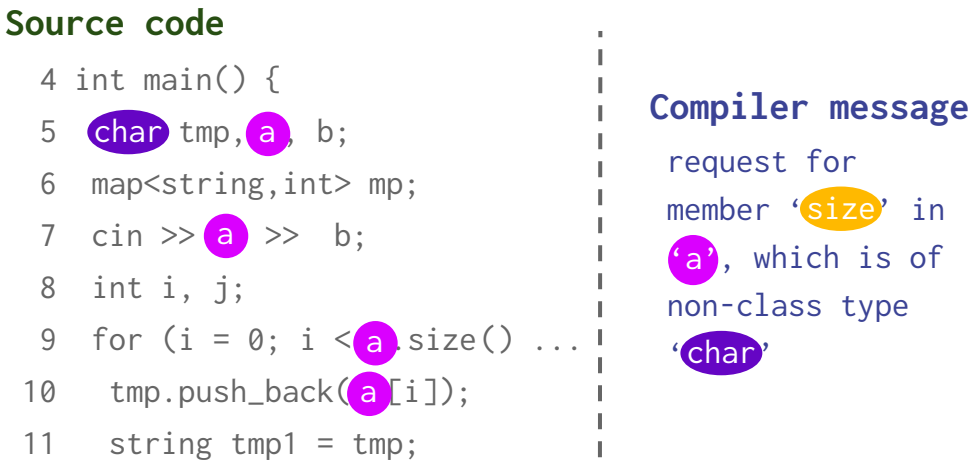

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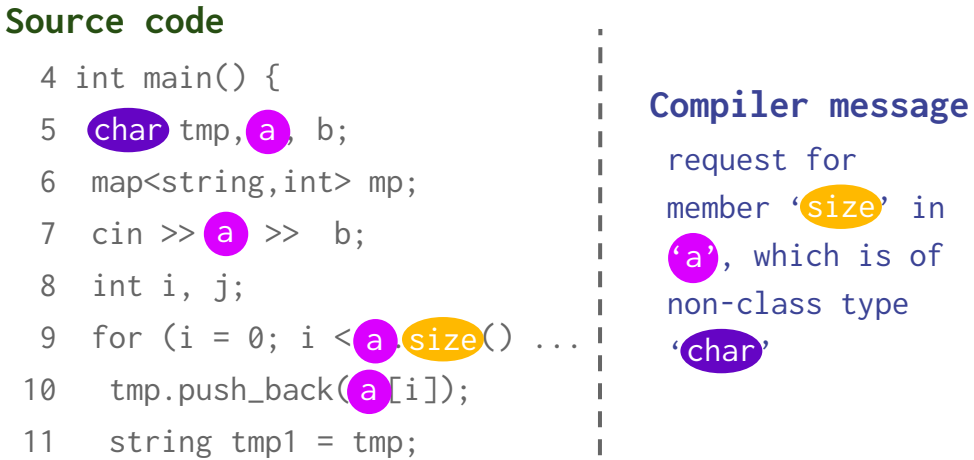
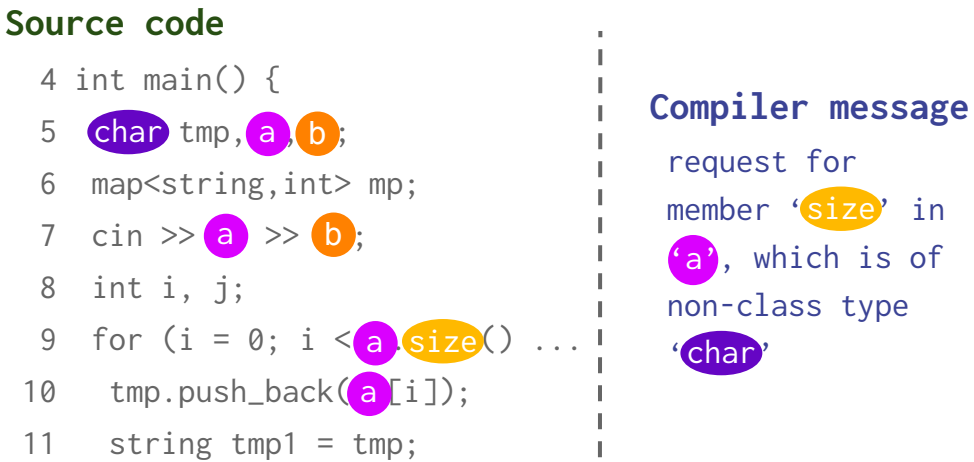


1. Reasoning via program-feedback graph

How to construct graph?

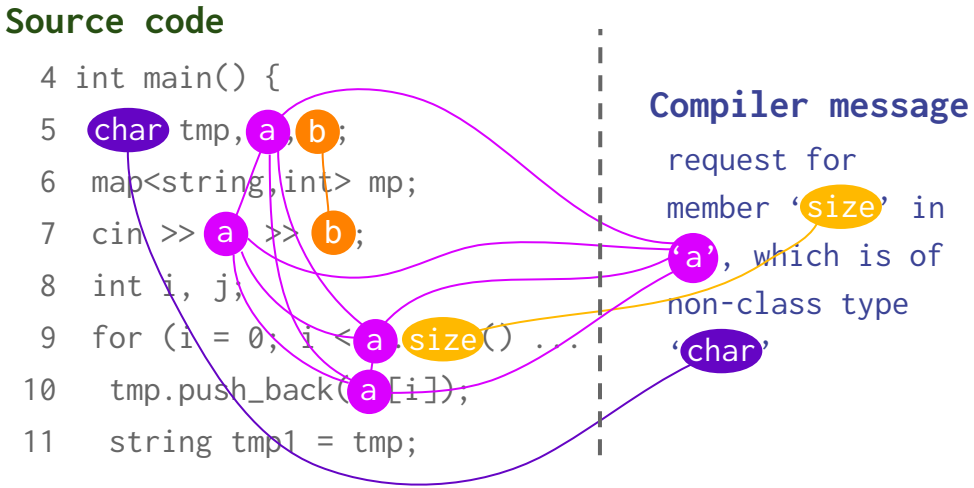
- Recognize token types
- **Nodes**: diagnostic arguments, their occurences, and all identifiers



1. Reasoning via program-feedback graph

How to construct graph?

- Recognize token types
- **Nodes**: diagnostic arguments, their occurences, and all identifiers
- **Edges**: connect identical tokens to capture semantic correspondence



1. Reasoning via program-feedback graph

Model

- Initial encoding
- Graph attention
- Recontextualization
- Decoding

1. Reasoning via program-feedback graph

Model (Initial encoding)

Source code

```
1  int main() {
2  char tmp, a, b;
3  map<string,int> mp;
...
```

Compiler message

```
9: request for member
   ‘size’ …
```

1. Reasoning via program-feedback graph

Model (Initial encoding)

Source code

```
1  int main() {
2  char tmp, a, b;
3  map<string,int> mp;
...
```

Line 1

Compiler message

```
9: request for member
   ‘size’ …
```

1. Reasoning via program-feedback graph

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1. Reasoning via program-feedback graph

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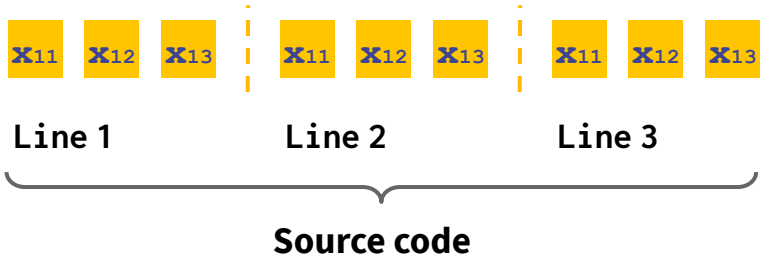

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1. Reasoning via program-feedback graph

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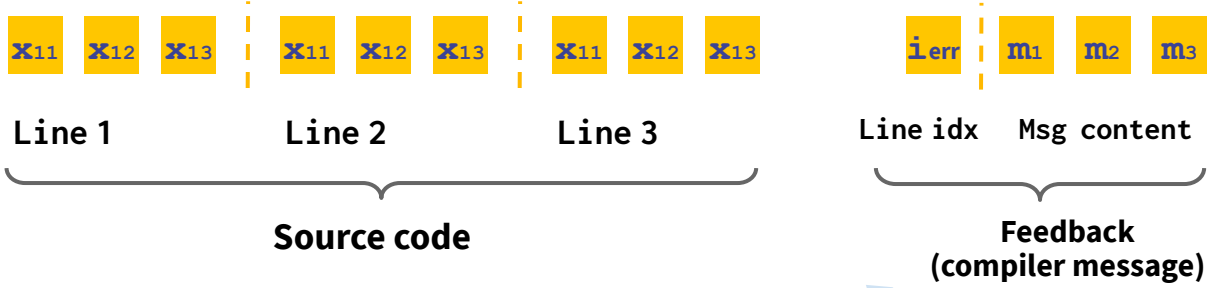

1. Reasoning via program-feedback graph

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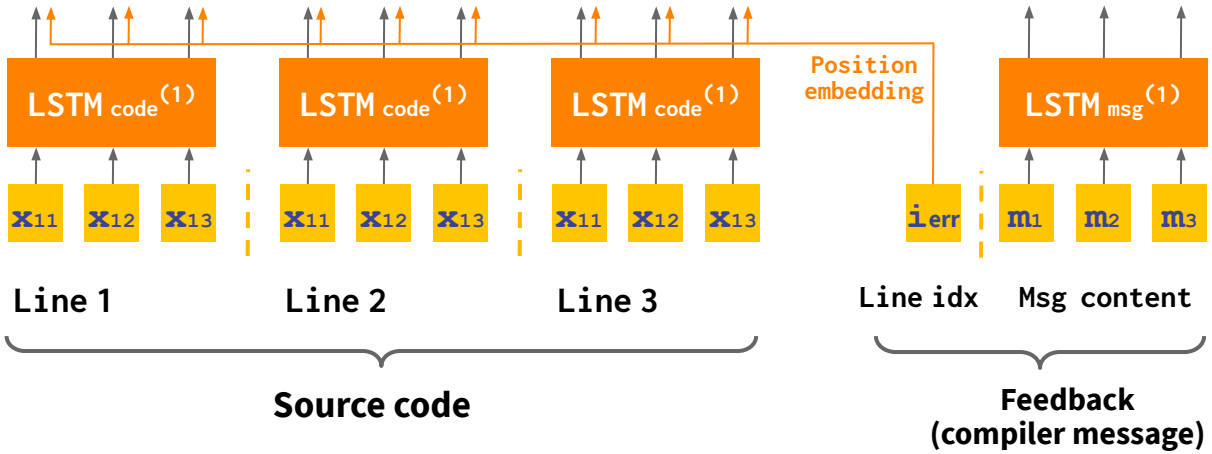

1. Reasoning via program-feedback graph

Model (Graph attention)

Source code

```
1  int main() {
2  char tmp, a, b;
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...
```

Compiler message

```
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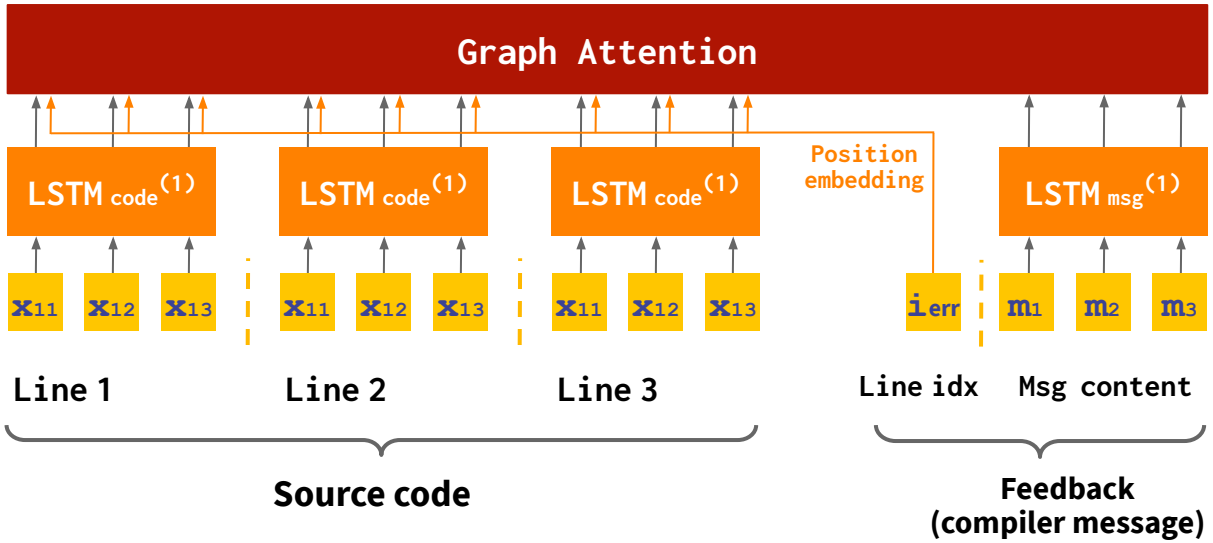

1. Reasoning via program-feedback graph

Model (Graph attention)

- Message passing across tokens with **long-range dependencies**

Source code

```
1  int main() {
2  char tmp, a, b;
3  map<string,int> mp;
...
```

Compiler message

```
9: request for member
   'size' …
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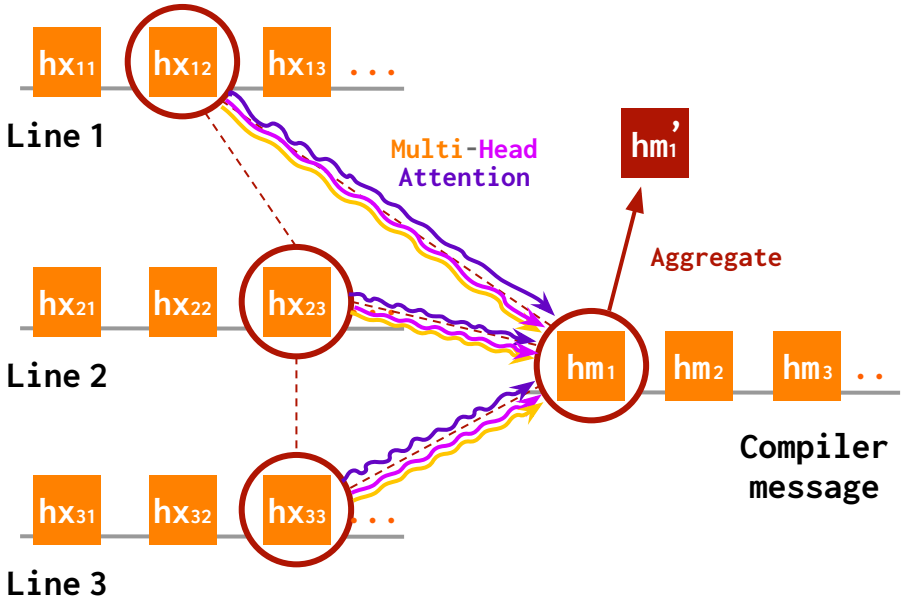

Program-Feedback Graph

1. Reasoning via program-feedback graph

Model (Graph attention)

Source code

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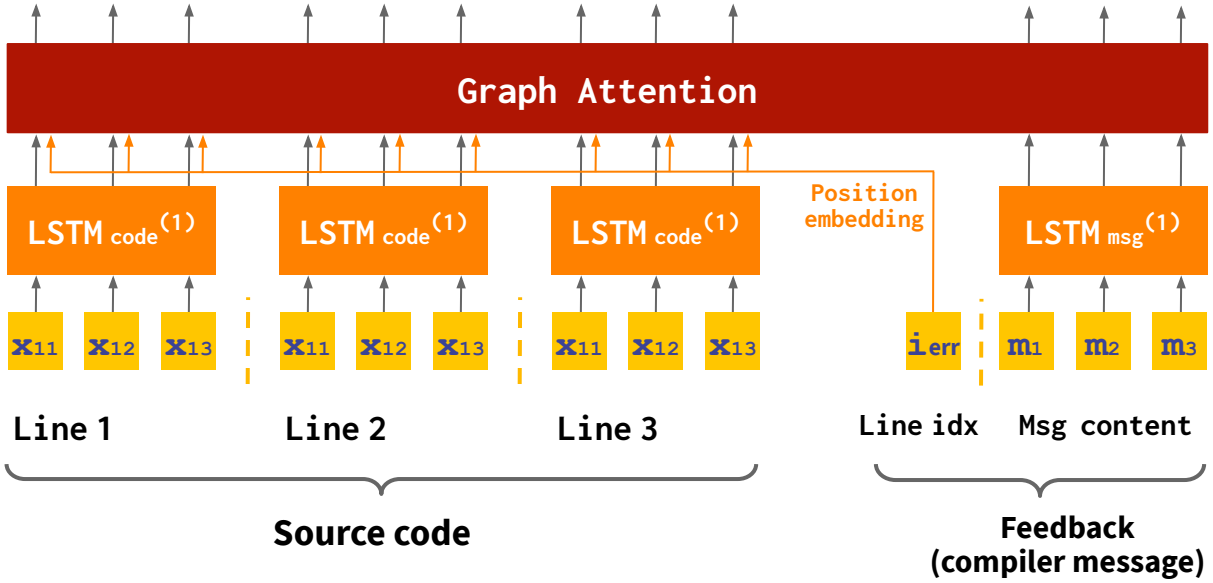

1. Reasoning via program-feedback graph

Model (Recontextualization)

Source code

```
1  int main() {
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3  map<string,int> mp;
...
```
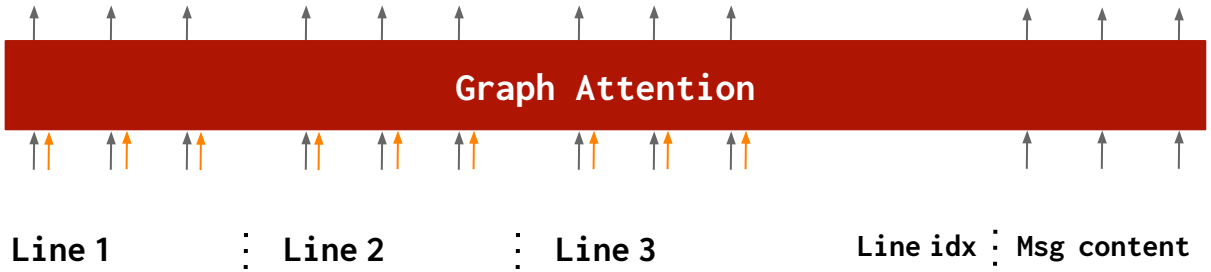

Compiler message

```
9: request for member
   ‘size’ …
```



1. Reasoning via program-feedback graph

Model (Recontextualization)

Source code

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3  map<string,int> mp;
...
```

Compiler message

```
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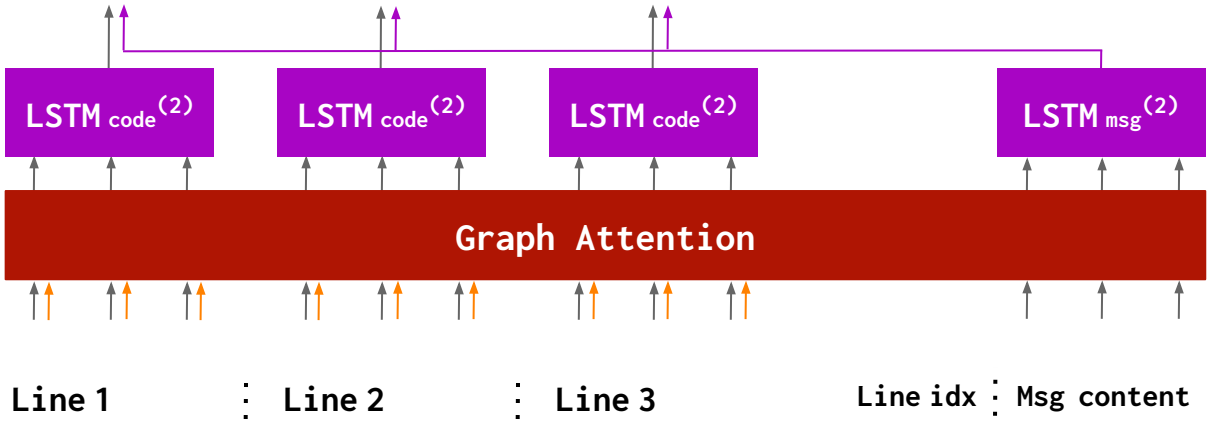

1. Reasoning via program-feedback graph

Model (Recontextualization)

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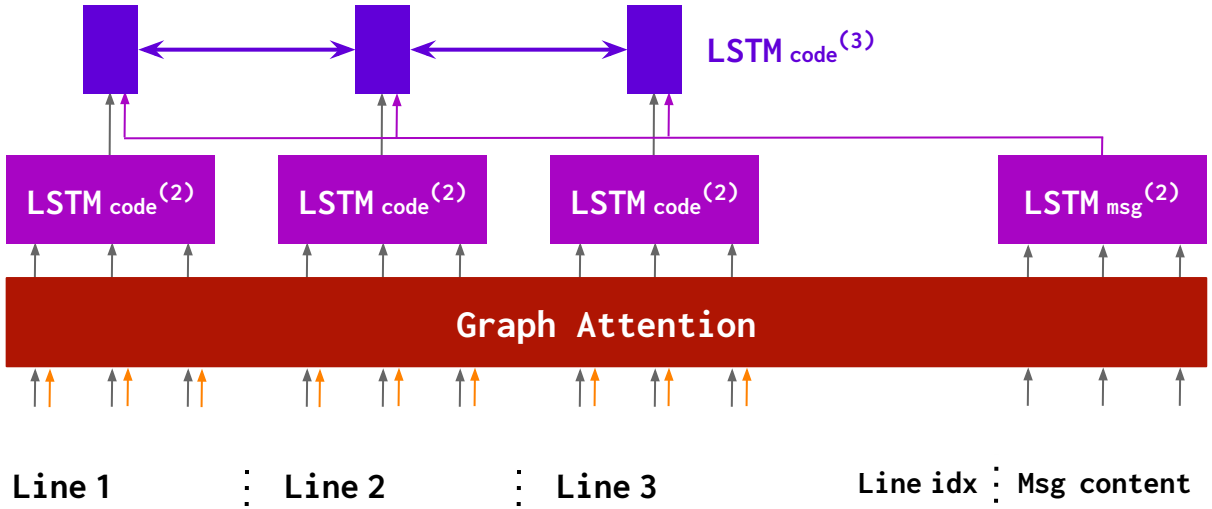

1. Reasoning via program-feedback graph

Model (Decoding)

Source code

```
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...
```

Compiler message

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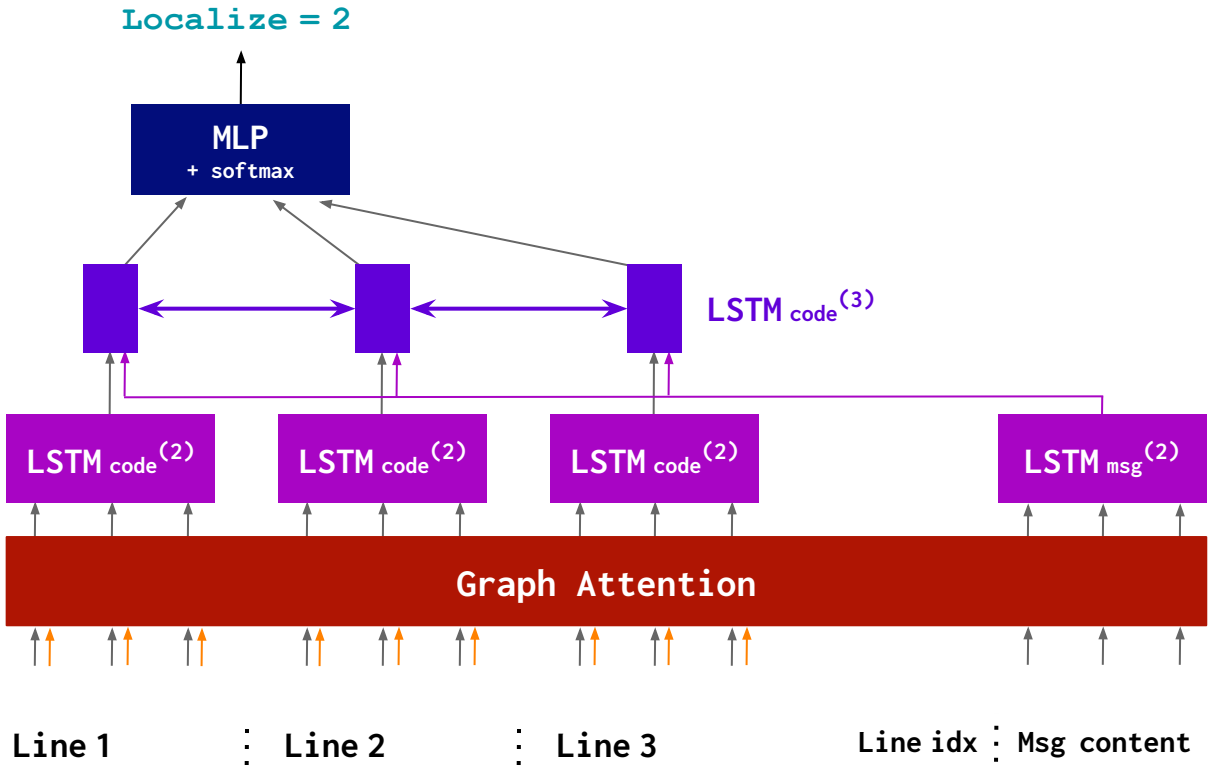

1. Reasoning via program-feedback graph

Model (Decoding)

Source code

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...
```

Compiler message

```
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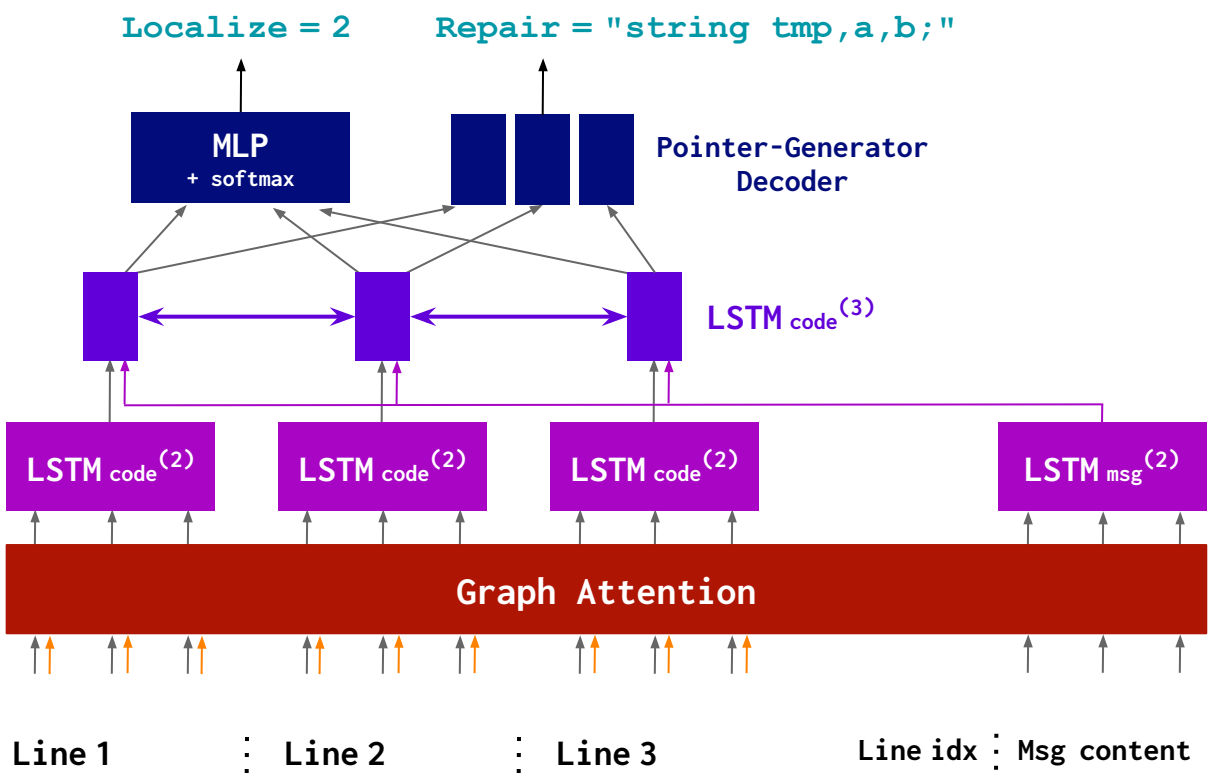
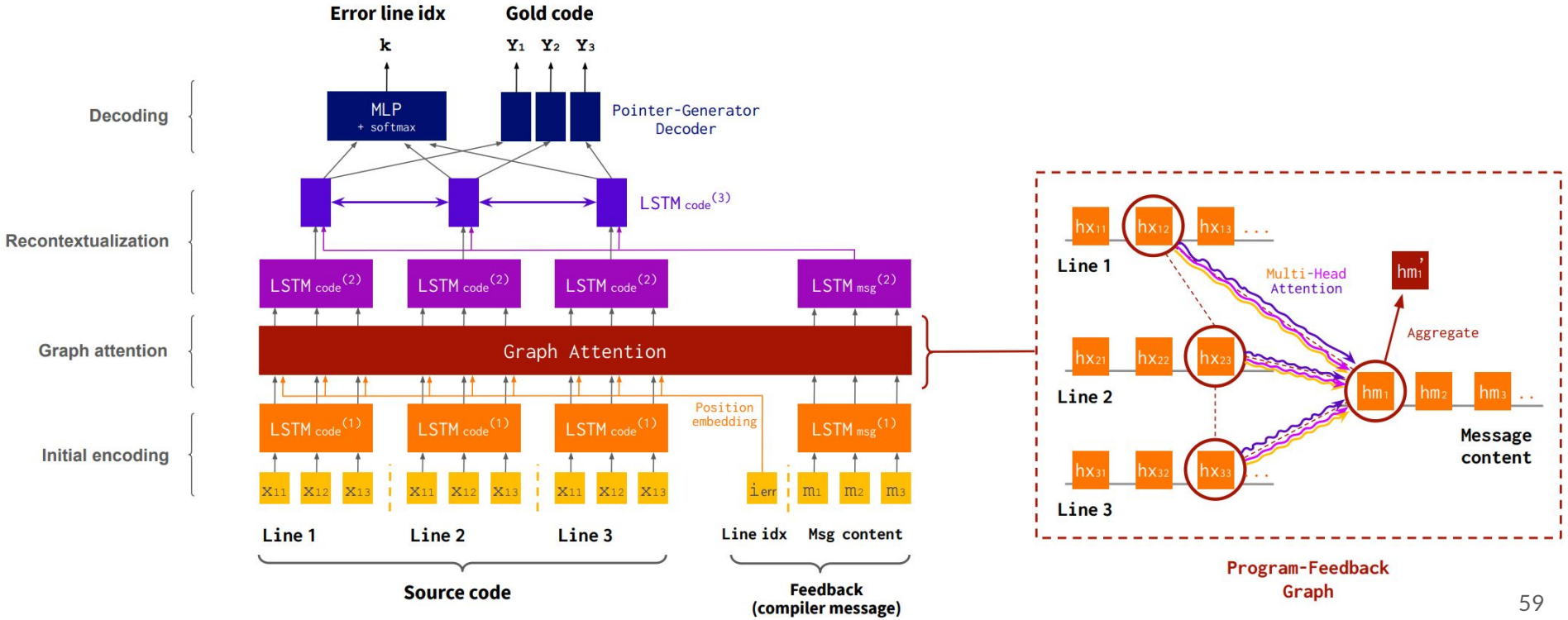


1. Reasoning via program-feedback graph

Model overview



2. Self-supervised learning

2. Self-supervised learning

Why?

- Labeled datasets of program repair are small (10-100K examples)
- Vast amount of **unlabeled programs** available online
- Can we leverage them to improve learning?

> 30M repos

>> 1M submissions

2. Self-supervised learning

Our idea (outline)

Step 1. Collect unlabeled, working programs **y**

Step 2. Design (randomized) program corruption procedure ***P***

Step 3. Corrupt and get diagnostic feedback (e.g. run compiler)

⇒ **Extra training data**: <broken code **x**, feedback ***f***, fixed code **y**>

Step 4. Use them for pre-training

2. Self-supervised learning

1. **Collect unlabeled programs**

- Our target tasks (DeepFix & SPoC) are in C/C++
- Collect 300K working C++ programs from `codeforces.com`

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

Error type	Common compiler messages	Statistics			
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`				
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`				
Identifier **undeclared**	`@@@ was not declared`				
Others	`'else' without a previous 'if'` `no matching function for call to...`				

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

Error type	Common compiler messages	Statistics			
		Experienced			
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`	9%			
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`	9%			
Identifier **undeclared**	`@@@ was not declared`	62%			
Others	`'else' without a previous 'if'` `no matching function for call to...`	20%			

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

Error type	Common compiler messages	Statistics			
		Experienced	Beginner		
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`	9%	48% • 37% • 11		
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`	9%	5%		
Identifier **undeclared**	`@@@ was not declared`	62%	33%		
Others	`'else' without a previous 'if'` `no matching function for call to...`	20%	14%		

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

Error type	Common compiler messages	Statistics			
		Experienced	Beginner	SPoC	
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`	9%	48% • 37% • 11	35% • 29% • 6%	
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`	9%	5%	18%	
Identifier **undeclared**	`@@@ was not declared`	62%	33%	31%	
Others	`'else' without a previous 'if'` `no matching function for call to...`	20%	14%	16%	

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

Error type	Common compiler messages	Statistics			
		Experienced	Beginner	SPoC	**Avg.**
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`	9%	48% • 37% • 11	35% • 29% • 6%	**30%** • **23%** • **7%**
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`	9%	5%	18%	**11%**
Identifier **undeclared**	`@@@ was not declared`	62%	33%	31%	**42%**
Others	`'else' without a previous 'if'` `no matching function for call to...`	20%	14%	16%	**17%**

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors (know your enemy)

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		Experienced	Beginner	SPoC	**Avg.**
Expected ... • operator/punctuator • primary expression	`expected @@@ (e.g. expected ';' before...)` `missing @@@ (e.g. missing ")`	9%	48% • 37% • 11	35% • 29% • 6%	**30%** • **23%** • **7%**
Identifier **type**	`redeclaration/conflicting declaration` `invalid conversion from <type> to <type>`	9%	5%	18%	**11%**
Identifier **undeclared**	`@@@ was not declared`	62%	33%	31%	**42%**
Others	`'else' without a previous 'if'` `no matching function for call to...`	20%	14%	16%	**17%**

[Gupta et al. 17] [Mesbah et al. 19] [Kulal et al. 19]

2. Self-supervised learning

2. **How to design corruption procedure P?**
   - Look at common errors
   - Design perturbation modules M to cause those errors

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors
- Design perturbation modules *M* to cause those errors

Perturbation module	Example
Syntax `(delete/insert/replace operators .;(){}'"+, etc.)`	`return 0; }` → `return 0; } }`

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors
- Design perturbation modules *M* to cause those errors

Perturbation module	Example
Syntax (delete/insert/replace **operators** .;(){}'"+, etc.)	`return 0; }` → `return 0; } }`
ID-type (delete/insert/replace **type**)	`string tmp;` → `char tmp;`

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors
- Design perturbation modules *M* to cause those errors

Perturbation module	Example
Syntax (delete/insert/replace **operators** .;(){}'"+, etc.)	`return 0; }` → `return 0; } }`
ID-type (delete/insert/replace **type**)	`string tmp;` → `char tmp;`
ID-typo (delete/insert/replace **IDentifier**)	`int a, b=0, m;` → `int a, m;`

2. Self-supervised learning

2. How to design corruption procedure *P*?

- Look at common errors
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Perturbation module	Example
Syntax (delete/insert/replace **operators** .;(){}'"+, etc.)	`return 0; }` `→ return 0; } }`
ID-type (delete/insert/replace **type**)	`string tmp;` `→ char tmp;`
ID-typo (delete/insert/replace **IDentifier**)	`int a, b=0, m;` `→ int a, m;`
Keyword (delete/insert/replace **keyword/call**)	`if (n >= 0)` `→ while (n >= 0)`

2. Self-supervised learning

2. **Our corruption procedure *P***
   - Look at common errors
   - Design perturbation modules *M* to cause those errors
   - ***P***: Sample 1-5 modules from *M*, and apply to program sequentially

2. Self-supervised learning

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     e.g. `ID-type`, `ID-typo`, `Syntax`.

2. Self-supervised learning

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Working code

```
 5  int i, n;
 6  string A;
 7  cin >> n;
 8  A.resize(n);
 9  for(i=0;i<n;i++){
10   cin >> A[i];
11   cout << i; }
```

2. Self-supervised learning

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```

Perturbed 1

```
 5  int i, n;
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2. Self-supervised learning

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- Look at common errors
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- ***P***: Sample 1-5 modules from *M*, and apply to program sequentially

  e.g. `ID-type`, `ID-typo`, `Syntax`.

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Perturbed 1

```
 5  int i, n;
 6  char A;
 7  cin >> n;
 8  A.resize(n);
 9  for(i=0;i<n;i++){
10   cin >> A[i];
11   cout << i; }
```

Perturbed 2

```
 5  int i, n;
 6  char A;
 7  cin >> n;
 8  A.resize(n);
 9  for(i=0;i<n;i++){
10   cin >> A[j];
11   cout << i; }
```

2. Self-supervised learning

2. Our corruption procedure *P*

- Look at common errors
- Design perturbation modules *M* to cause those errors
- ***P***: Sample 1-5 modules from *M*, and apply to program sequentially

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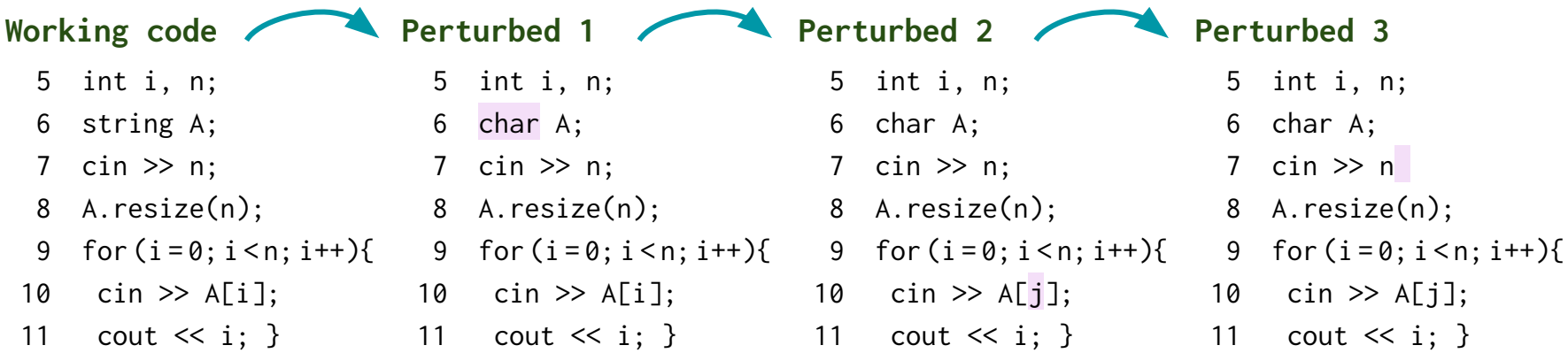

2. Self-supervised learning

3. **Prepare pre-training data**
   - 300K working programs from **codeforces.com**

Working code

```
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2. Self-supervised learning

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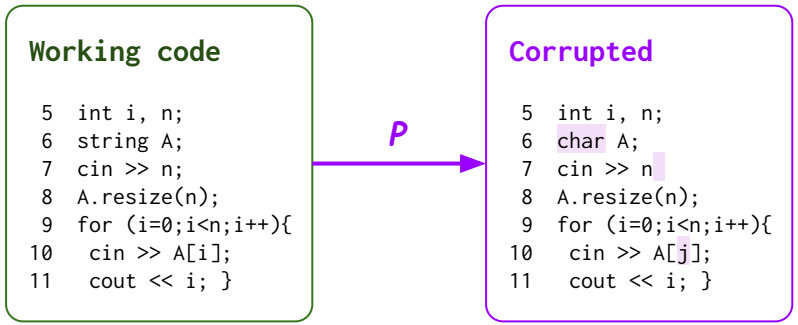

2. Self-supervised learning

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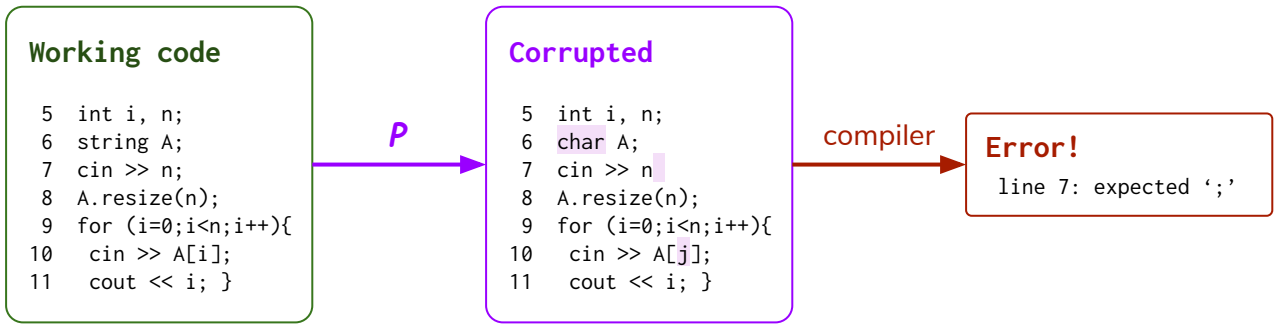

2. Self-supervised learning

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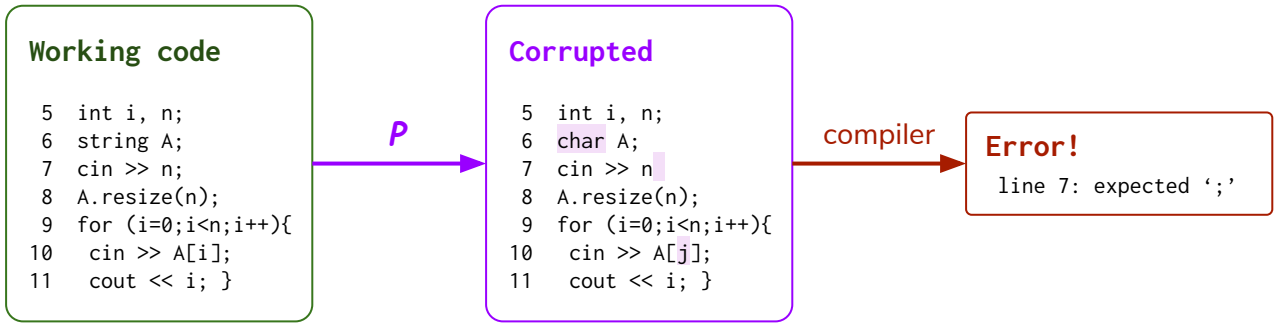
     ⇒ New program repair examples: <broken code, feedback, fixed code>



2. Self-supervised learning

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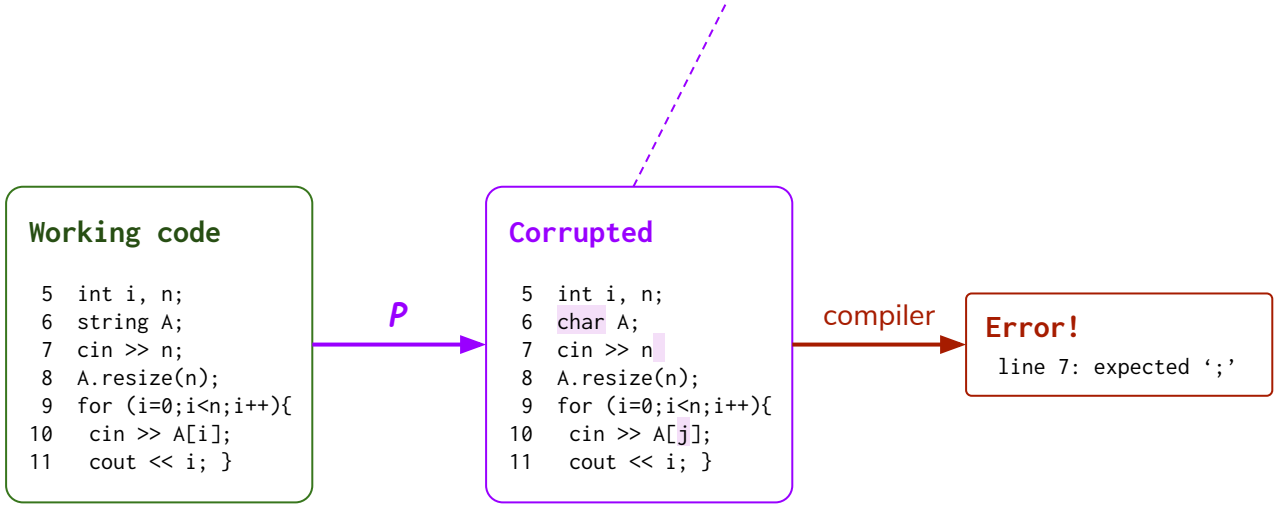

2. Self-supervised learning

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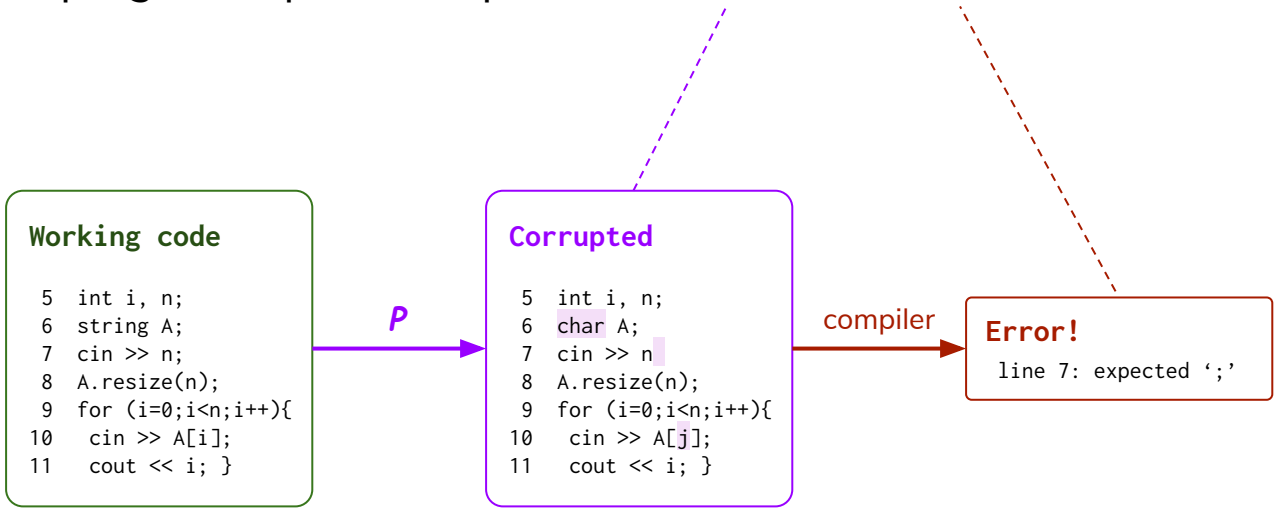

2. Self-supervised learning

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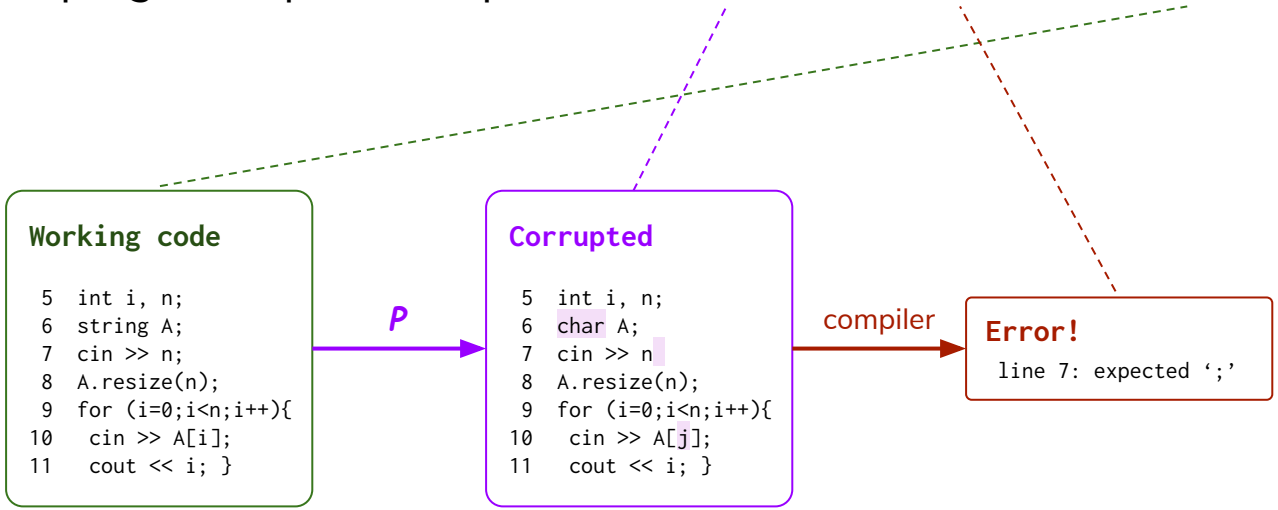

2. Self-supervised learning

What's interesting?

- Typically, pre-training **task** ≠ target **task** (e.g. masked LM v.s. QA)
- Here, **targeted** pre-training (pre-training **task** = target **task** = program repair)
  - More direct pre-training structure
  - **Data** distributions can be different between pre-training & target

Evaluation 1: DeepFix

Evaluation 1: DeepFix

Task

- Repair C programs
- May have **multiple error lines**
- Apply repair model iteratively (up to 5 times)

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  int pow(int a, int b);
4  int main(){
5   int n;
6   scanf("%d",&n);
7   int i, j;
8   for(i=1;i<=n;i++){
9    for(j=0;j<=n;j++){
10    if(j<i){
11     printf("%d ",pow(i,j));}}
12   printf("\n");}
13  return 0;}
```

[Gupta et al., 17]

Evaluation 1: DeepFix

Our model outputs

Input code

```
 4 int main() {
 5  int n;
 6  int * m[2];
 7  m[0] = malloc(n*sizeof(int));
 8  m[1] = malloc(n*sizeof(int));
 9  for (i = 0; i < n; i++) {
10   m[0][i] = -1;
11   m[1][i] = -1; }
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```

Evaluation 1: DeepFix

Our model outputs

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 9  for (i = 0; i < n; i++) {
10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 }
```

Error message

```
line 9: ‘i’ undeclared
```

Evaluation 1: DeepFix

Our model outputs

DrRepair

Input code

```
 4 int main() {
 5  int n;
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 7  m[0] = malloc(n*sizeof(int));
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10   m[0][i] = -1;
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```

Attempt 1

```
 4 int main() {
 5  int n, i;
 6  int * m[2];
 7  m[0] = malloc(n*sizeof(int));
 8  m[1] = malloc(n*sizeof(int));
 9  for (i = 0; i < n; i++) {
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12  return 0 }
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line 9: ‘i’ undeclared
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Our model outputs

DrRepair

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 4 int main() {
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Error message

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line 9: ‘i’ undeclared
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11   m[1][i] = -1; }
12  return 0 }
```

Error message

```
line 12: expected ‘;’ before
‘}’
```

Evaluation 1: DeepFix

Our model outputs

DrRepair

DrRepair

Input code

```
 4 int main() {
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 7  m[0] = malloc(n*sizeof(int));
 8  m[1] = malloc(n*sizeof(int));
 9  for (i = 0; i < n; i++) {
10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 }
```

Error message

```
line 9: ‘i’ undeclared
```

Attempt 1

```
 4 int main() {
 5  int n, i;
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10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 }
```

Error message

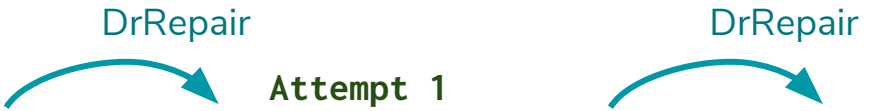
```
line 12: expected ‘;’ before
‘}’
```

Attempt 2

```
 4 int main() {
 5  int n;
 6  int * m[2];
 7  m[0] = malloc(n*sizeof(int));
 8  m[1] = malloc(n*sizeof(int));
 9  for (i = 0; i < n; i++) {
10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 ; }
```

Evaluation 1: DeepFix

Our model outputs



Input code

```
 4 int main() {
 5  int n;
 6  int * m[2];
 7  m[0] = malloc(n*sizeof(int));
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Error message

line 9: ‘i’ undeclared

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10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 }
```

Error message

line 12: expected ‘;’ before ‘}’

Attempt 2

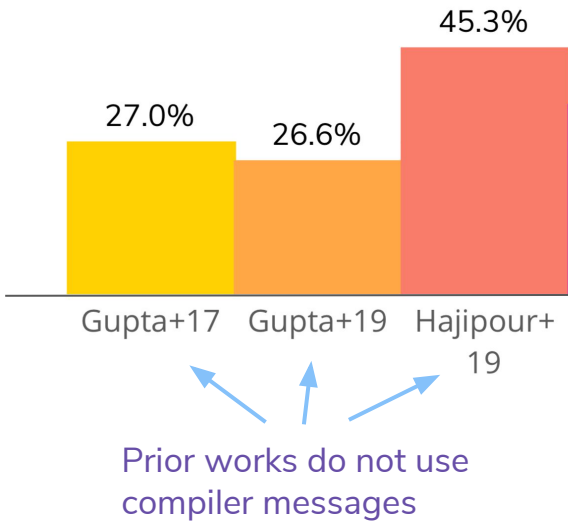
```
 4 int main() {
 5  int n;
 6  int * m[2];
 7  m[0] = malloc(n*sizeof(int));
 8  m[1] = malloc(n*sizeof(int));
 9  for (i = 0; i < n; i++) {
10   m[0][i] = -1;
11   m[1][i] = -1; }
12  return 0 ; }
```

Compiled!!

Evaluation 1: DeepFix

Results

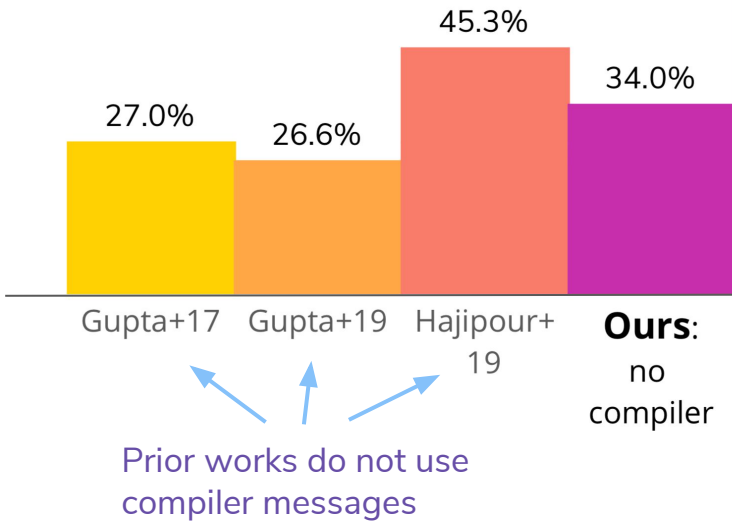
Test (full repair accuracy)



Evaluation 1: DeepFix

Results

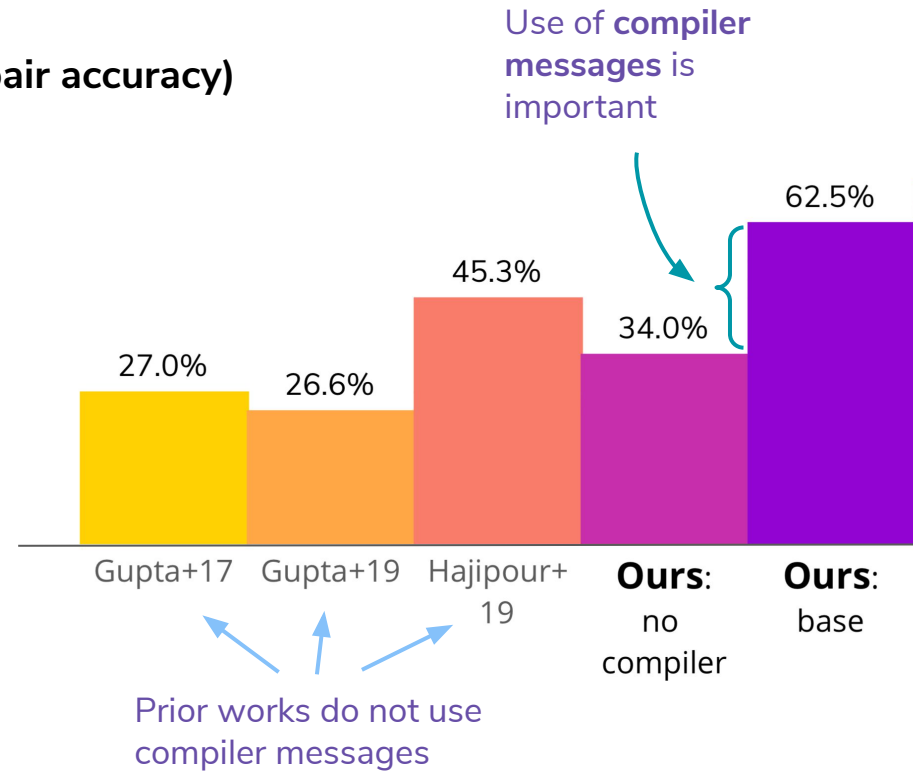
Test (full repair accuracy)



Evaluation 1: DeepFix

Results

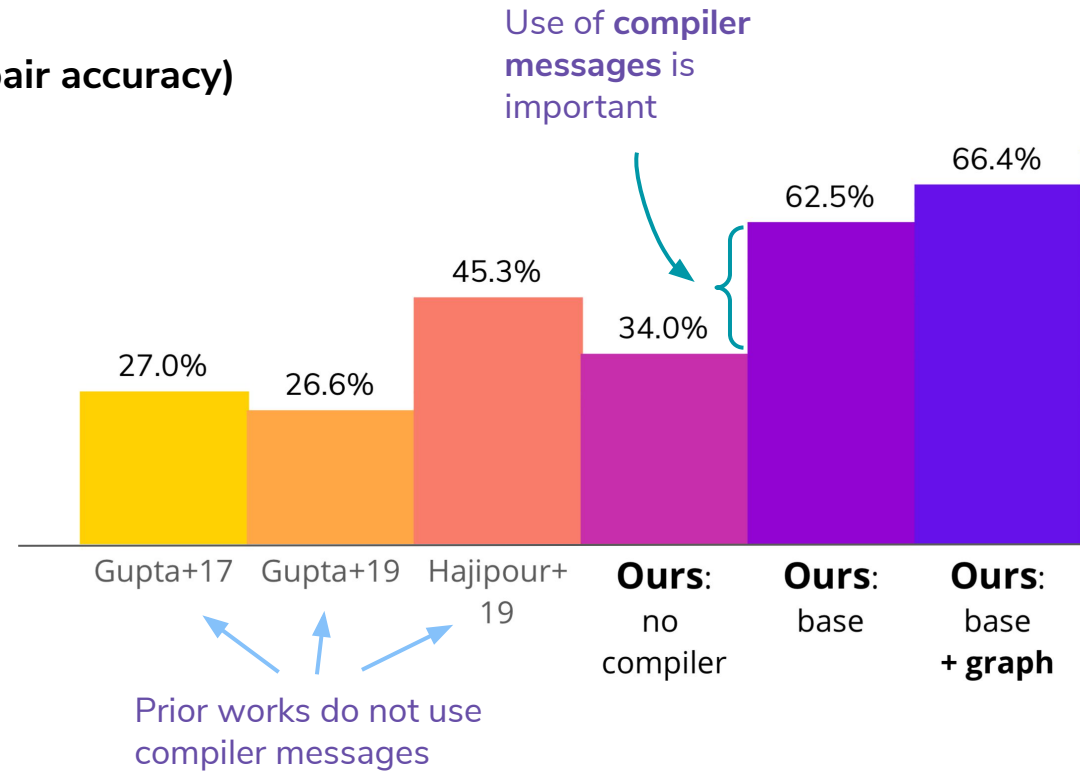
Test (full repair accuracy)



Evaluation 1: DeepFix

Results

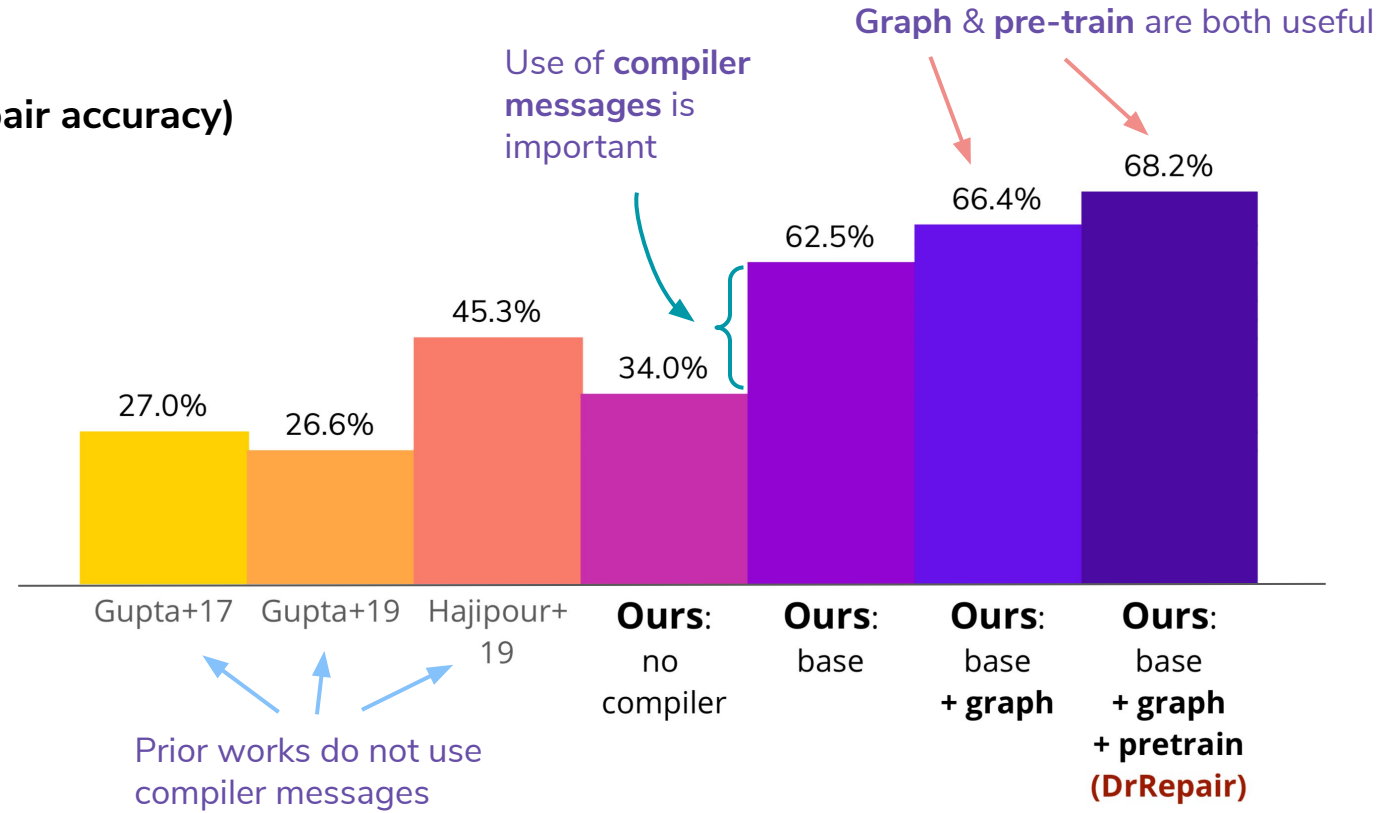
Test (full repair accuracy)



Evaluation 1: DeepFix

Results

Test (full repair accuracy)

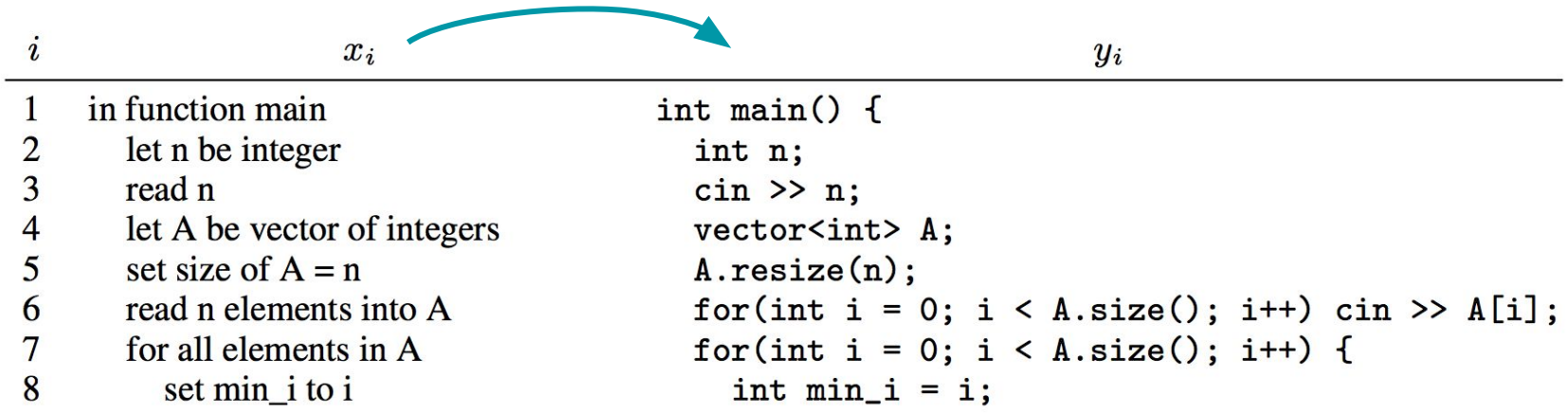


Evaluation 2: SPoC

Evaluation 2: SPoC

Task

- Translate pseudocode into C++ code (**program synthesis**)
- Line-level alignment



i	x_i	y_i
1	in function main	`int main() {`
2	let n be integer	`int n;`
3	read n	`cin >> n;`
4	let A be vector of integers	`vector<int> A;`
5	set size of A = n	`A.resize(n);`
6	read n elements into A	`for(int i = 0; i < A.size(); i++) cin >> A[i];`
7	for all elements in A	`for(int i = 0; i < A.size(); i++) {`
8	set min_i to i	`int min_i = i;`

[Kulal et al., 19]

Evaluation 2: SPoC

Prior work (Kulal+19)

- Stitch line-level translations & search

Pseudocode

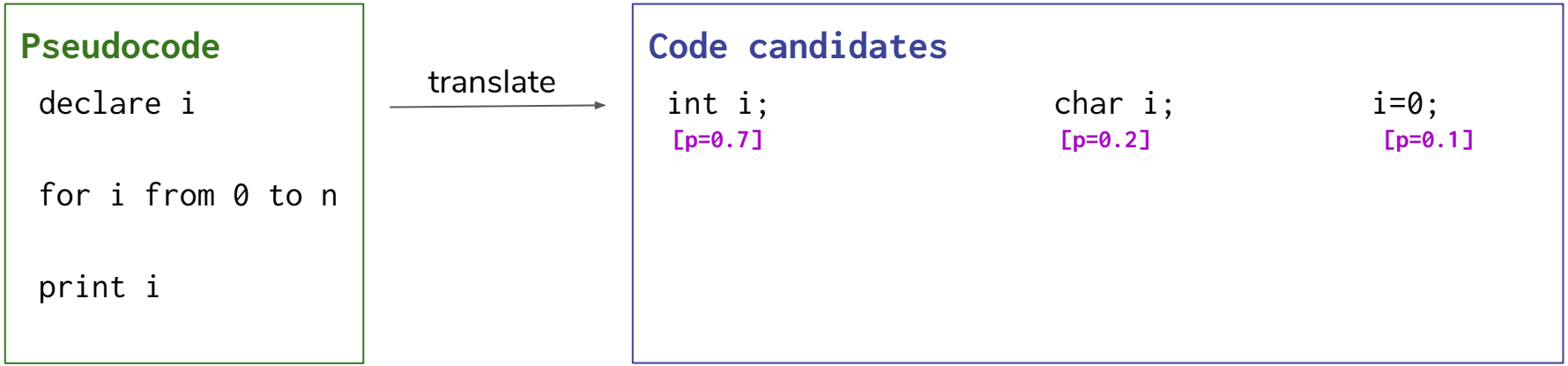
```
declare i

for i from 0 to n

print i
```

Code candidates

Evaluation 2: SPoC

Prior work (Kulal+19)

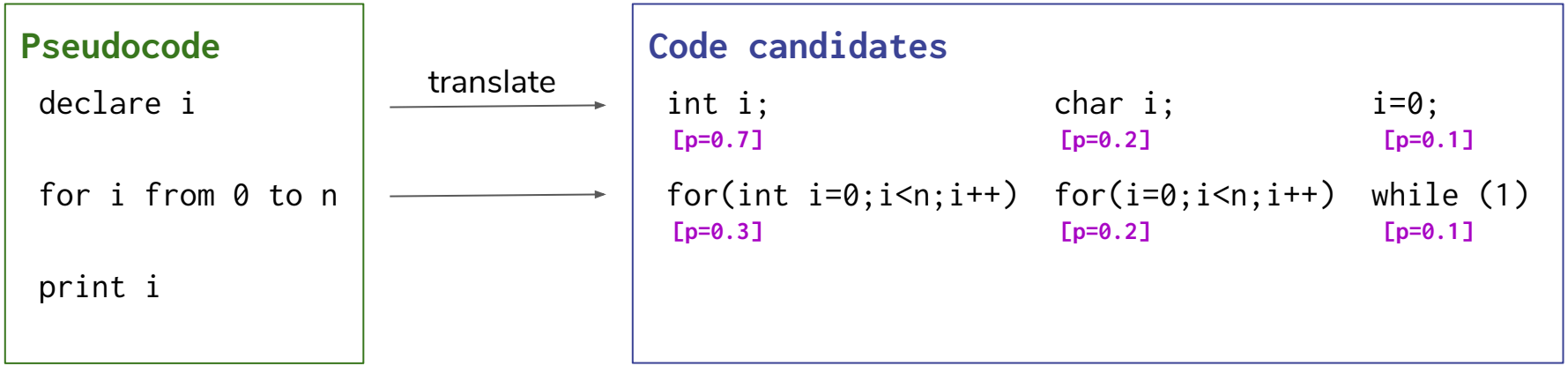
- Stitch line-level translations & search



Evaluation 2: SPoC

Prior work (Kulal+19)

- Stitch line-level translations & search



Evaluation 2: SPoC

Prior work (Kulal+19)

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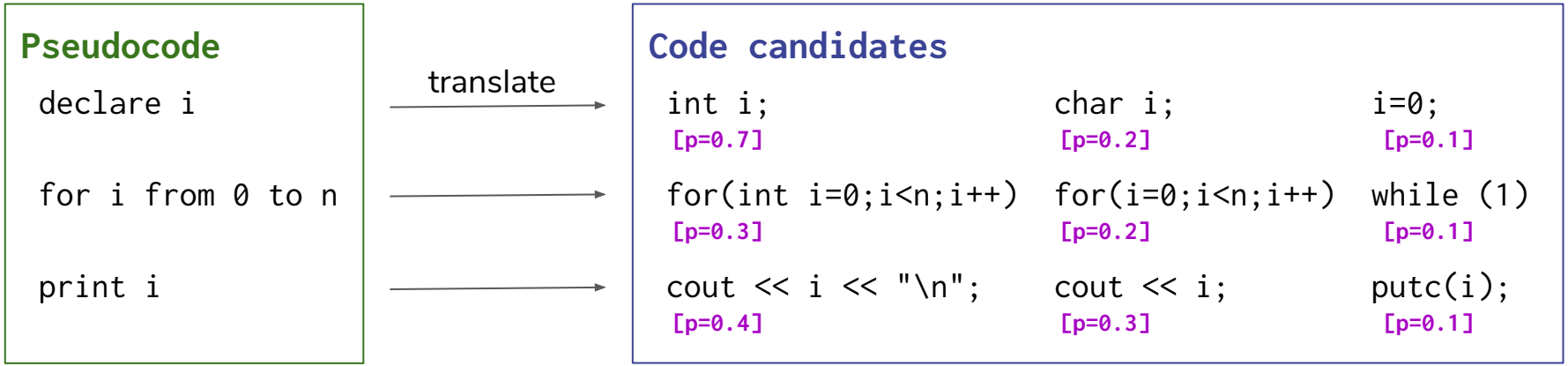
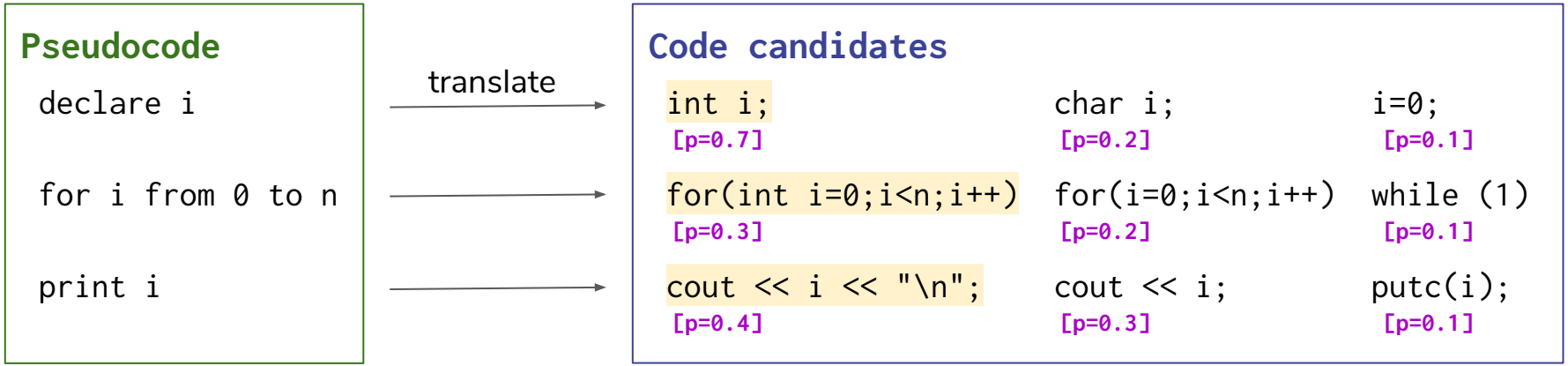


Evaluation 2: SPoC

Prior work (Kulal+19)

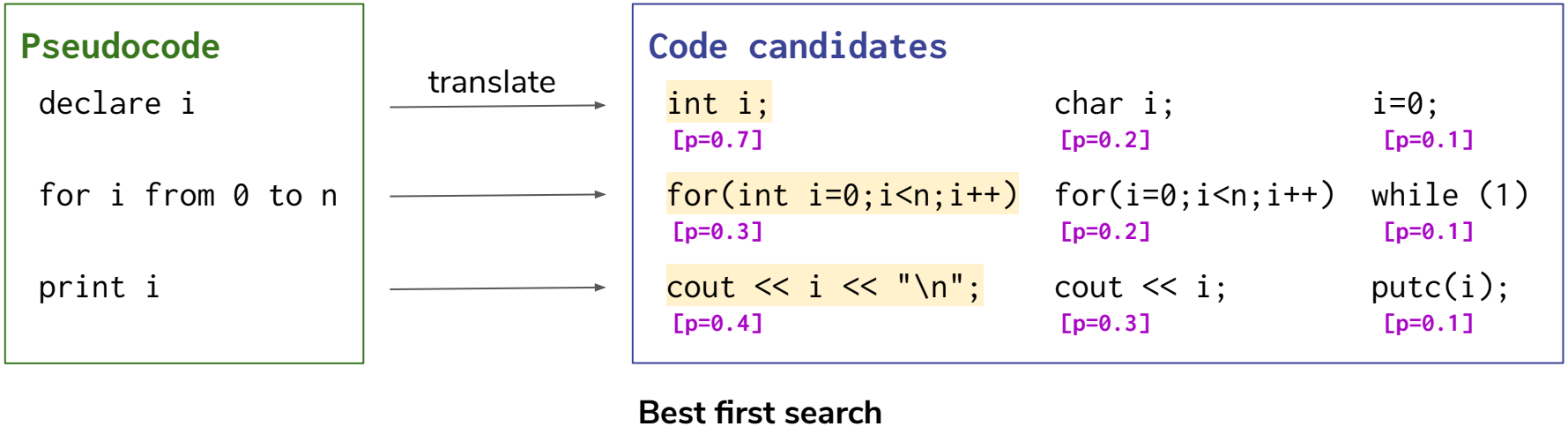
- Stitch line-level translations & search



Evaluation 2: SPoC

Prior work (Kulal+19)

- Stitch line-level translations & search

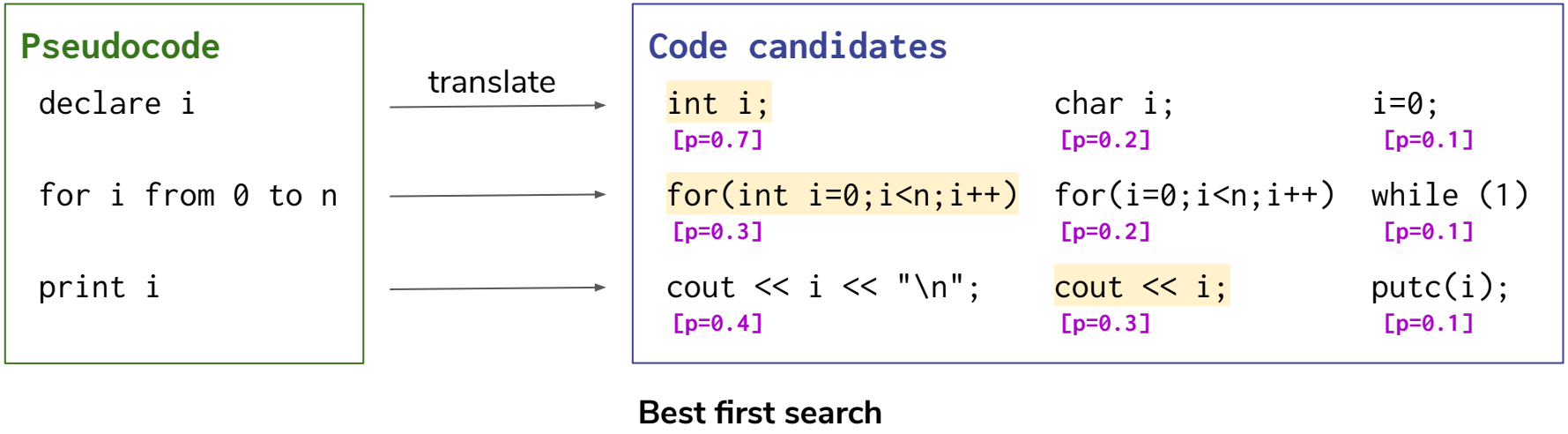


Best first search

Evaluation 2: SPoC

Prior work (Kulal+19)

- Stitch line-level translations & search

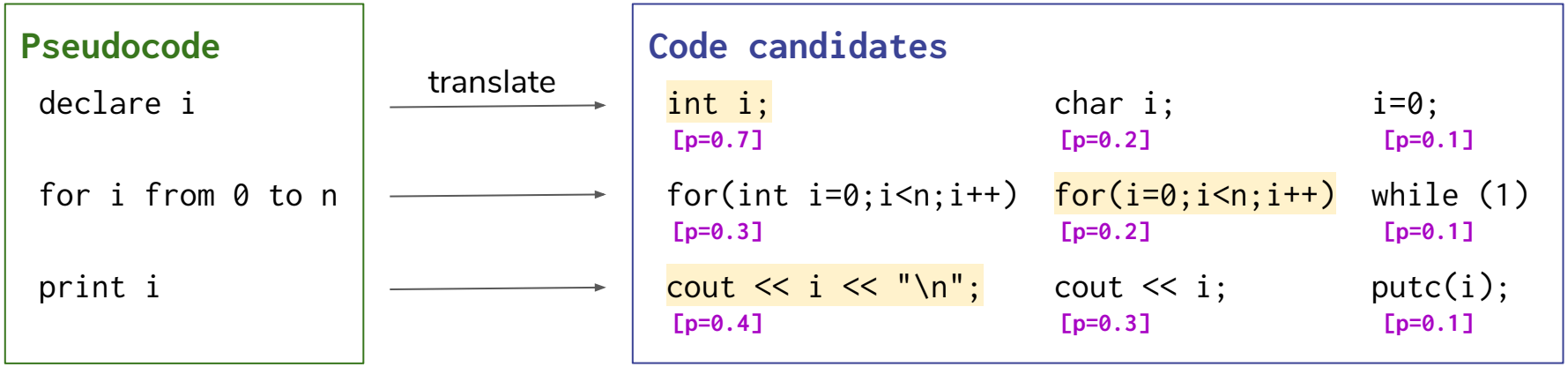


Best first search

Evaluation 2: SPoC

Prior work (Kulal+19)

- Stitch line-level translations & search



Best first search ...

Evaluation 2: SPoC

Problem

- Line-level translation misses global context

Code candidates

`int i;` [p=0.7]	`char i;` [p=0.2]	`i=0;` [p=0.1]
`for(int i=0;i<n;i++)` [p=0.3]	`for(i=0;i<n;i++)` [p=0.2]	`while (1)` [p=0.1]
`cout << i << "\n";` [p=0.4]	`cout << i;` [p=0.3]	`putc(i);` [p=0.1]

Evaluation 2: SPoC

Problem

- Line-level translation misses global context

Code candidates

`int i;` [p=0.7]	`char i;` [p=0.2]	`i=0;` [p=0.1]
`for(int i=0;i<n;i++)` [p=0.3]	`for(i=0;i<n;i++)` [p=0.2]	`while (1)` [p=0.1]
`cout << i << "\n";` [p=0.4]	`cout << i;` [p=0.3]	`putc(i);` [p=0.1]

→ **Does not compile!**
(redeclaration of ‘i’)

Evaluation 2: SPoC

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- Line-level translation misses global context

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`int i;` [p=0.7]	`char i;` [p=0.2]	`i=0;` [p=0.1]
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→ **Does not compile!**
(redeclaration of ‘i’)

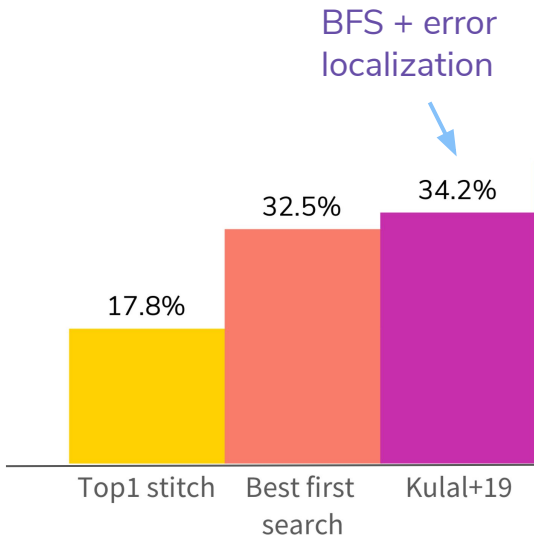
Our solution

- Apply repair model if current candidate program does not compile

Evaluation 2: SPoC

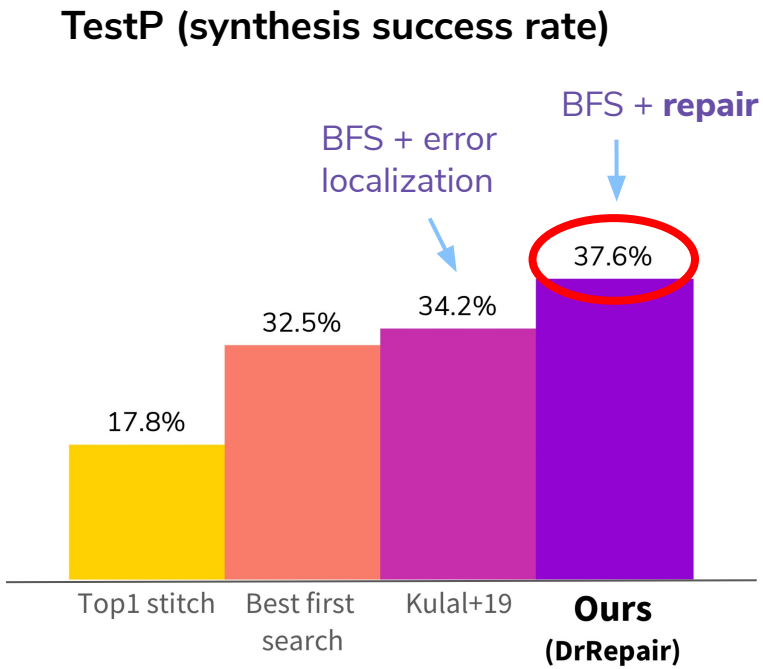
Results

TestP (synthesis success rate)



Evaluation 2: SPoC

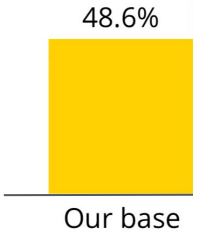
Results



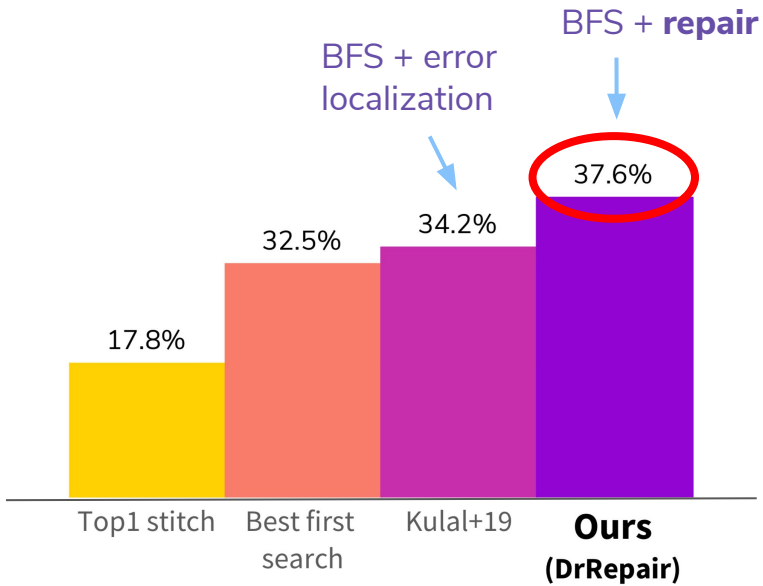
Evaluation 2: SPoC

Results

Dev (repair accuracy) - ablation



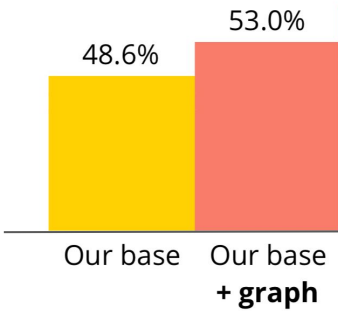
TestP (synthesis success rate)



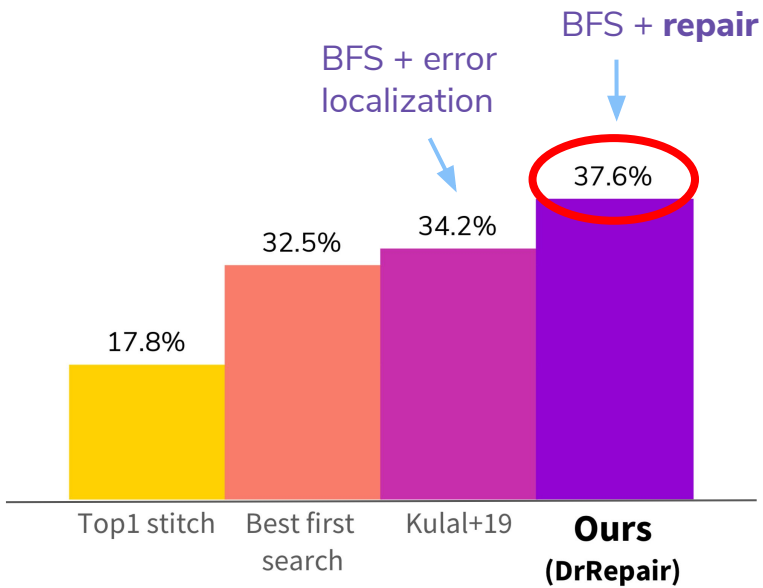
Evaluation 2: SPoC

Results

Dev (repair accuracy) - ablation



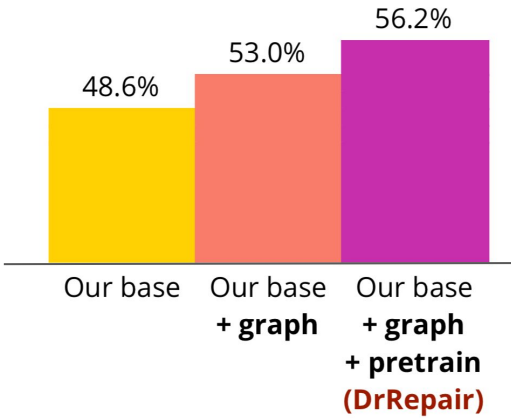
TestP (synthesis success rate)



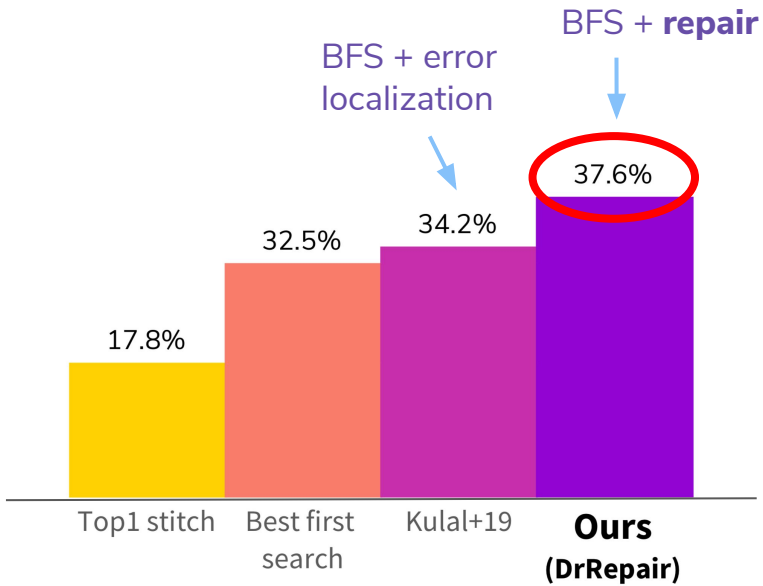
Evaluation 2: SPoC

Results

Dev (repair accuracy) - ablation



TestP (synthesis success rate)



Evaluation 2: SPoC

Results

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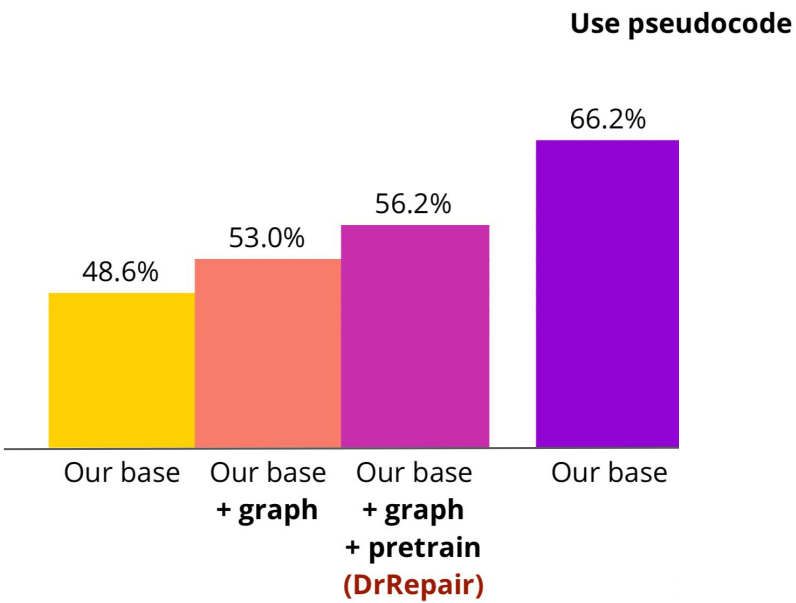

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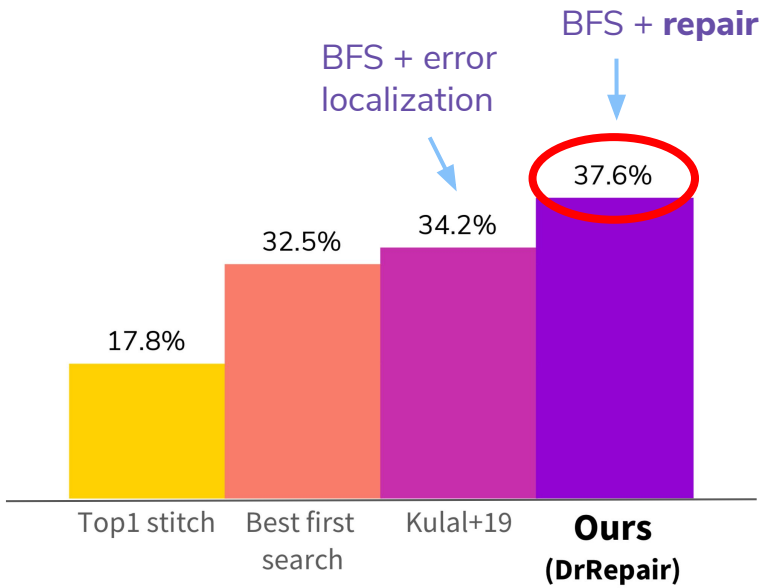

Evaluation 2: SPoC

Results

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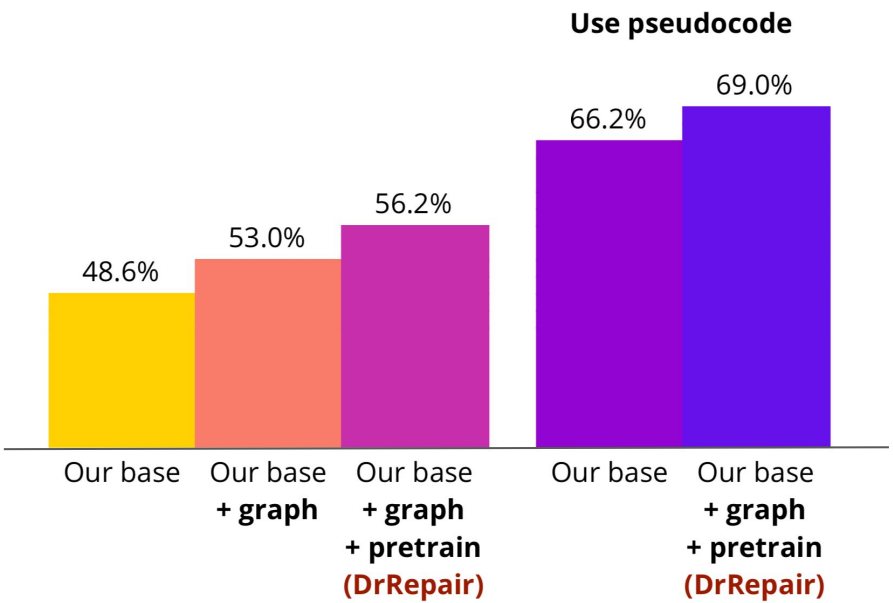
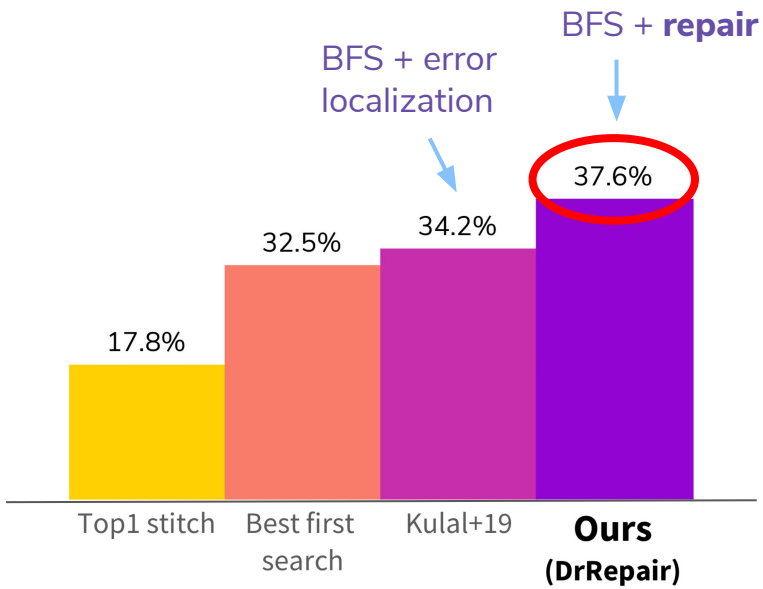


TestP (synthesis success rate)



Analysis 1: When is **graph** useful?

Compiler message type	Frequency in train set (SPoC)	Repair acc. (SPoC dev)		
		base	+ graph	+ graph + pretrain
`‘@@@’ was not declared …`	35.2 %	50.2	58.9	65.0
`redeclaration of ‘@@@’`	8.9 %	40.7	43.0	49.1
`expected ‘@@@’ before ‘@@@’`	3.2 %	67.6	70.7	86.1
`expected primary-expression before …`	3.0 %	47.4	47.4	49.1
`request for member ‘@@@’ in ‘@@@’, …`	2.9 %	37.9	56.9	48.4
`expected initializer before ‘@@@’`	2.1 %	48.8	50.1	93.0
`‘@@@’ without a previous ‘@@@’`	1.3 %	37.0	38.7	44.4

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Analysis 1: When is **graph** useful?

Need reasoning over multiple lines of code

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`expected initializer before ‘@@@’`	2.1 %	48.8	50.1	93.0
`‘@@@’ without a previous ‘@@@’`	1.3 %	37.0	38.7	44.4

Recall this example

Broken program

```
1  #include <bits/stdc++.h>
2  #include <string>
3  using namespace std;
4  int main() {
5    char tmp, a, b;
6    map<string,int> mp;
7    cin >> a >> b;
8    int i, j;
9    for (i = 0; i < a.size(); i++){
10     tmp.push_back(a[i]);
11     string tmp1 = tmp;
12     for (j = 0; j < b.size(); j++){
13       tmp1.push_back(b[j]);
14       mp[tmp1] = 1;
15     }
16   } ...
```

Multi-hop!

Feedback

```
line 9:error: request for
member ‘size’ in ‘a’, which
is of non-class type ‘char’
```

Repair

1. Error localized **line 5**
2. Repair

```
  char tmp, a, b;
→ string tmp, a, b;
```

Analysis 1: When is **graph** useful?

Need reasoning over multiple lines of code

Graph captures **long-range connections** of tokens

Compiler message type	Frequency in train set (SPoC)	Repair acc. (SPoC dev)		
		base	+ graph	+ graph + pretrain
`‘@@@’ was not declared …`	35.2 %	50.2	**58.9**	65.0
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Analysis 2: When is **pre-training** useful?

Compiler message type	Frequency in train set (SPoC)	Repair acc. (SPoC dev)		
		base	+ graph	+ graph + pretrain
`‘@@@’ was not declared …`	35.2 %	50.2	**58.9**	65.0
`redeclaration of ‘@@@’`	8.9 %	40.7	**43.0**	49.1
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`request for member ‘@@@’ in ‘@@@’, …`	2.9 %	37.9	**56.9**	48.4
`expected initializer before ‘@@@’`	2.1 %	48.8	50.1	**93.0**
`‘@@@’ without a previous ‘@@@’`	1.3 %	37.0	38.7	**44.4**

Analysis 2: When is **pre-training** useful?

Rare in train set

Extra examples in pre-training are helpful

Compiler message type	Frequency in train set (SPoC)	Repair acc. (SPoC dev)		
		base	+ graph	+ graph + pretrain
`‘@@@’ was not declared …`	35.2 %	50.2	**58.9**	65.0
`redeclaration of ‘@@@’`	8.9 %	40.7	**43.0**	49.1
`expected ‘@@@’ before ‘@@@’`	3.2 %	67.6	70.7	86.1
`expected primary-expression before …`	3.0 %	47.4	47.4	49.1
`request for member ‘@@@’ in ‘@@@’, …`	2.9 %	37.9	**56.9**	48.4
`expected initializer before ‘@@@’`	**2.1 %**	48.8	50.1	**93.0**
`‘@@@’ without a previous ‘@@@’`	**1.3 %**	37.0	38.7	**44.4**

Takeaways

New insights

- Use of **error messages** is crucial to learn program repair
- Program-feedback **graph** helps complex reasoning
- Unlabeled programs can be used for **targeted pre-training**

General framework

- **Learning to reason with feedback** - many applications, e.g.
  - Edit essays based on written feedback
  - Learn from user inputs in interactive dialogue
- We show that **graph-based reasoning** can be a good solution

Thanks!

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Code/Data: https://cs.stanford.edu/~myasu/