南京大學
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Unveiling Compiler Faults via Attribute-Guided Compilation Space Exploration

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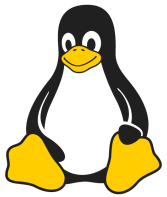
Compilers are fundamental to software system



Operating System Kernel

Database Management System

Android Application

Deep Learning Framework

.....

But compilers are prone to bugs

But compilers are prone to bugs

- Code complexity is high
- Support a wide range of platforms
- Optimization algorithm are complex

.....

But compilers are prone to bugs

Code complexity is high

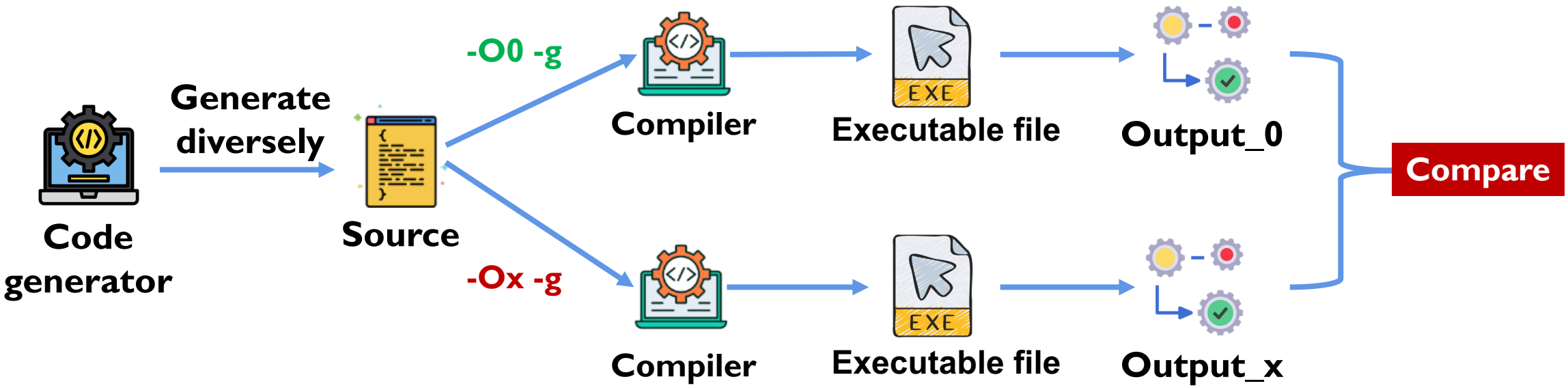
Support a wide range of platforms

Optimization algorithm are complex

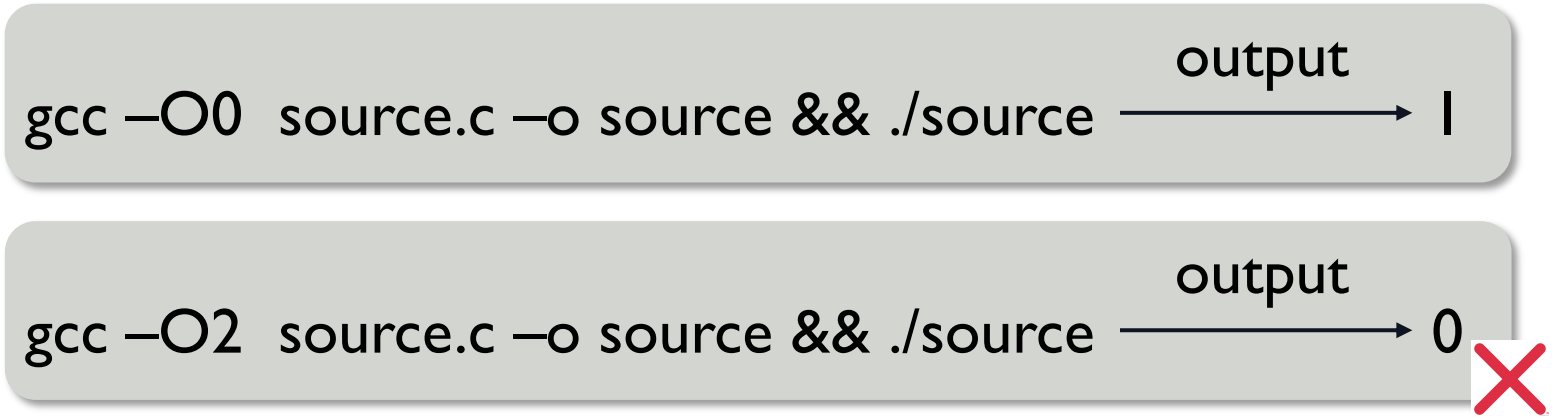
.....

Compiler bugs can seriously impact system correctness, ensuring compiler reliability and correctness is crucial

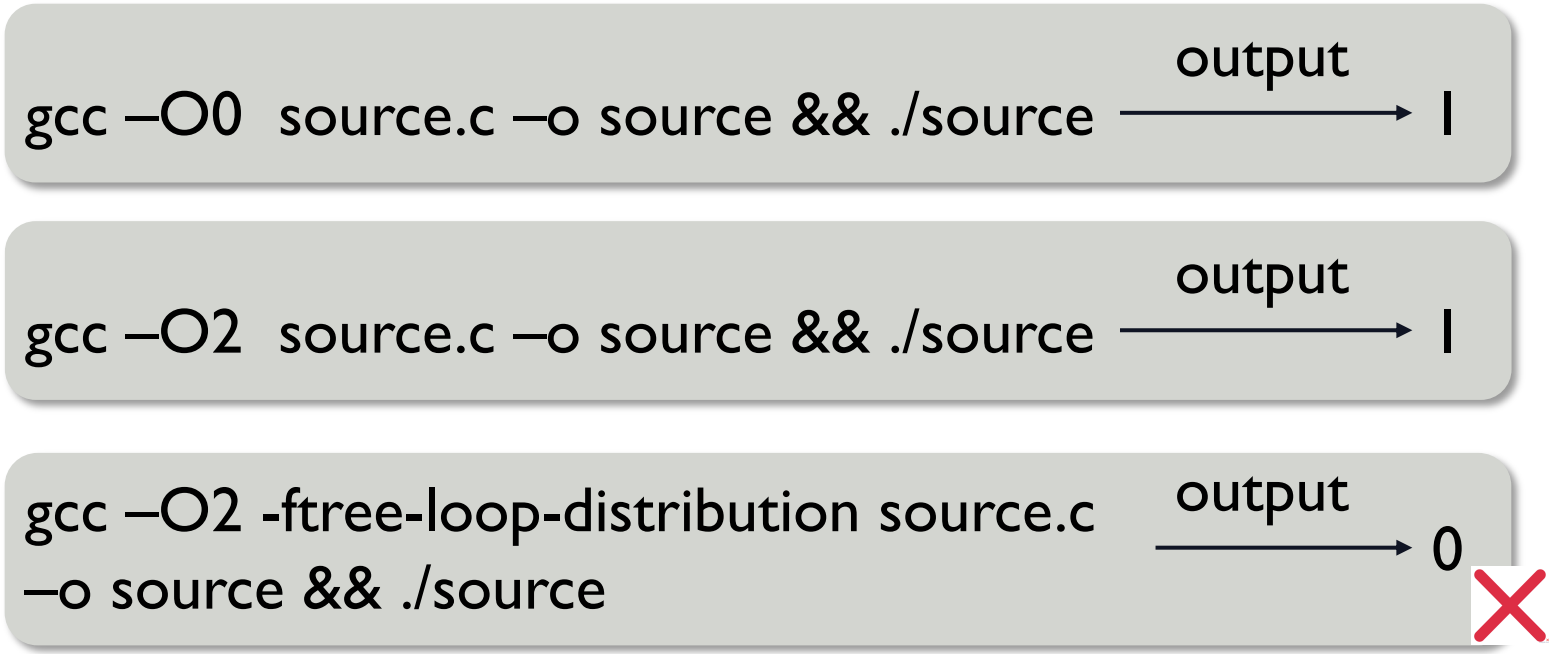
Existing approaches for compiler testing



Existing approaches for compiler testing



Existing approaches for compiler testing



Existing approaches for compiler testing

gcc –O0 source.c –o source && ./source → output: 1

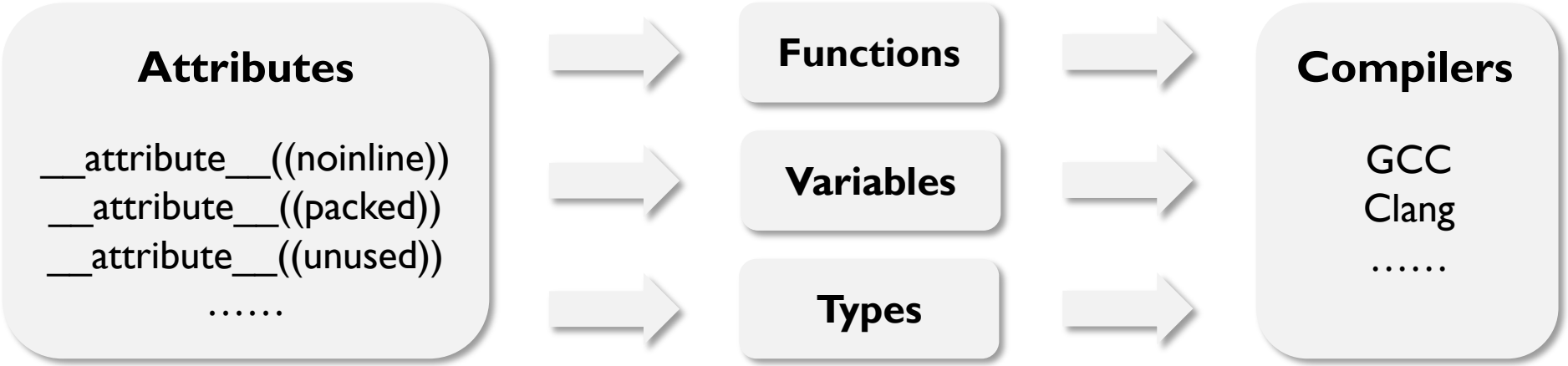
gcc –O2 source.c –o source && ./source → output: 1

gcc –O2 -ftree-loop-distribution source.c –o source && ./source → output: 0 ✗

Compiler options are typically applied to the entire program

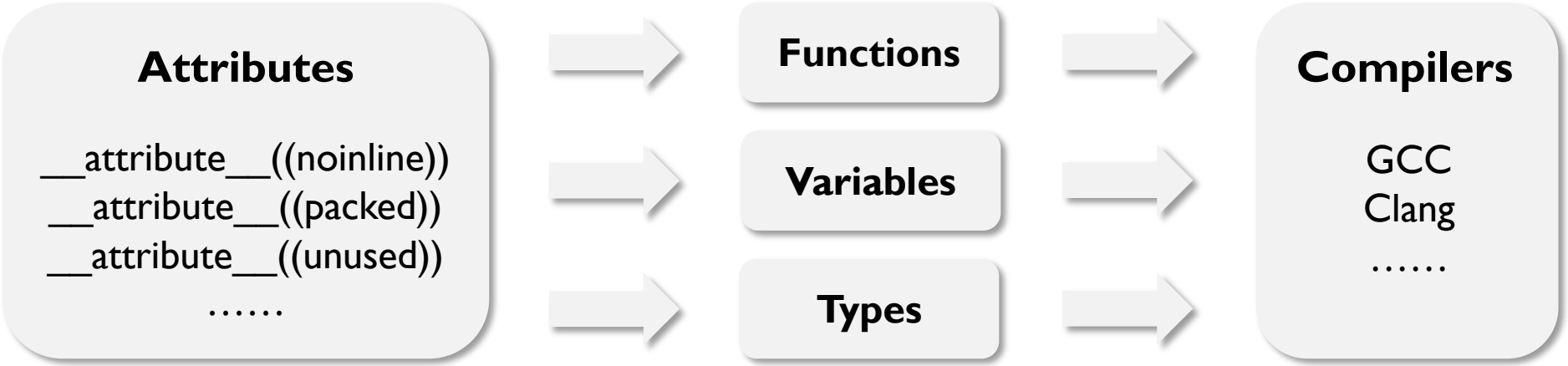
What is attribute?

Attributes give the compiler extra information about specific code elements



What is attribute?

Attributes provide the compiler extra information about specific code elements



Attributes enable fine-grained control over compilation behavior

A motivation example

```
struct S {
  int i;
};
inline struct S bar() {
  struct S s = { 0 };
  return s;
}
void foo() {
  bar();
}
```

Source Program

A motivation example

```
struct S {
  int i;
};
inline struct S bar() {
  struct S s = { 0 };
  return s;
}
__attribute__((optimize("-ftree-loop-distribution")))
void foo() {
  bar();
}
```

GCC Bug 43234

GCC crashed when compiled it with –O1

https://gcc.gnu.org/bugzilla/show_bug.cgi?id=43234

Another motivation example

```
int **a;
__attribute__((always_inline)) int *foo(void) {
  int b[1];
  (void) b;
}
__attribute__((no_sanitize_address)) static char
bar(void) {
  *a = foo();
}
void baz(void) {
  bar();
}
```

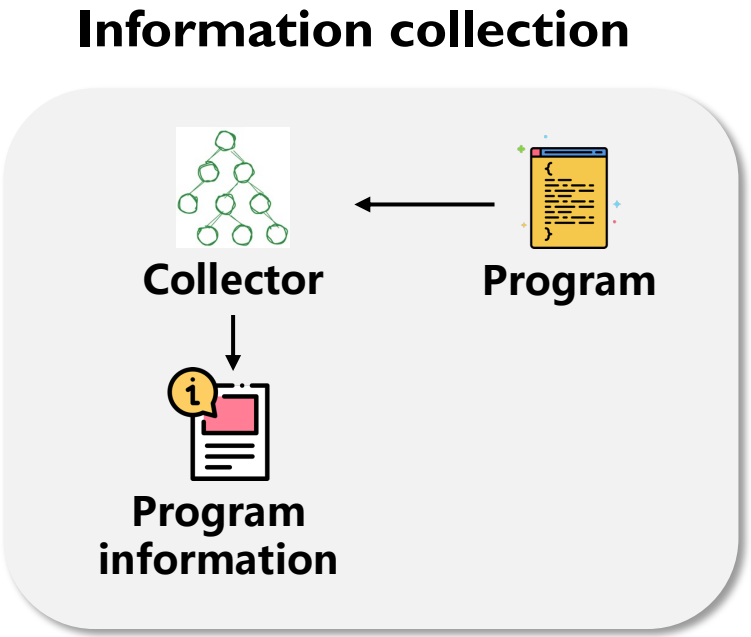
GCC Bug 114956

GCC crashed when compiled it with -O2 -fsanitize=address

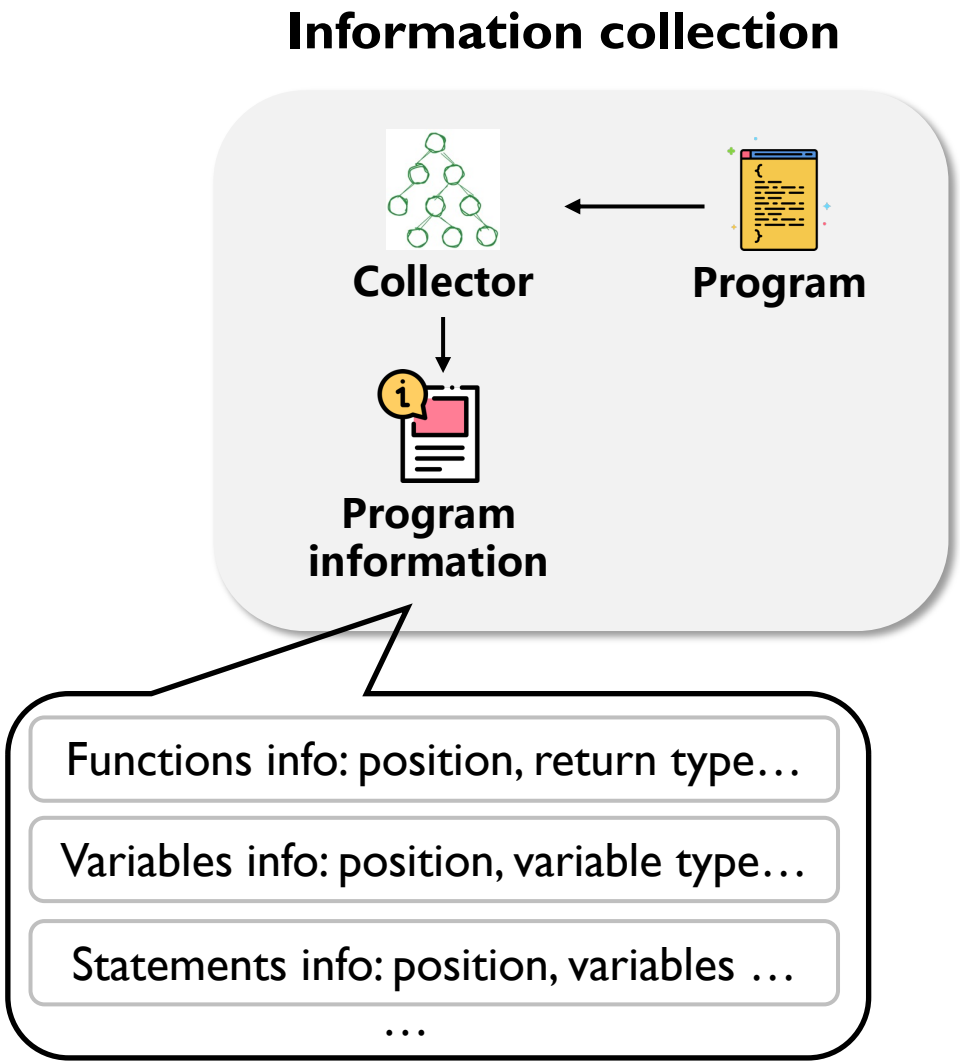
https://gcc.gnu.org/bugzilla/show_bug.cgi?id=114956

Atlas
Attribute-Guided Compilation Space Exploration

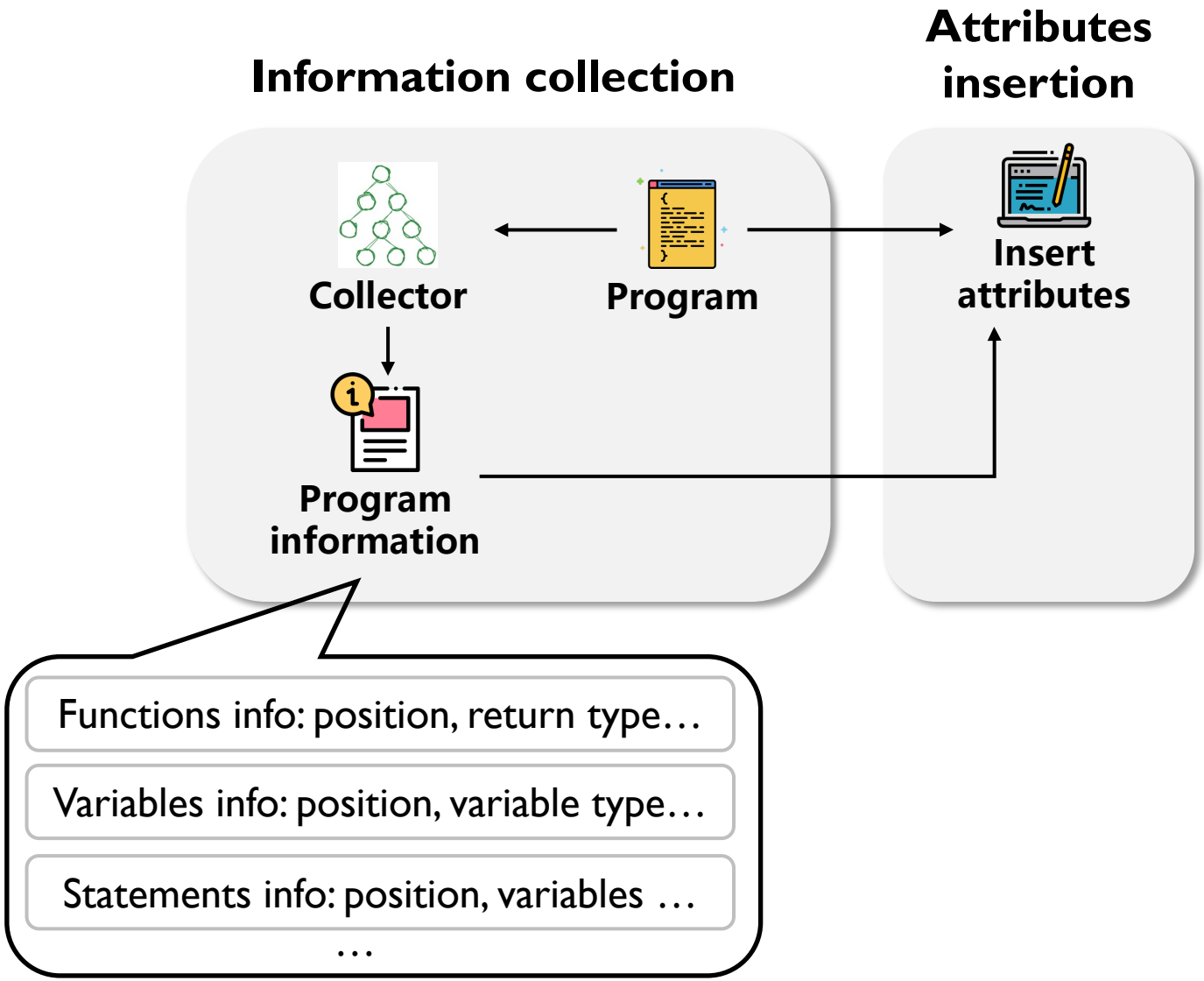
Atlas workflow



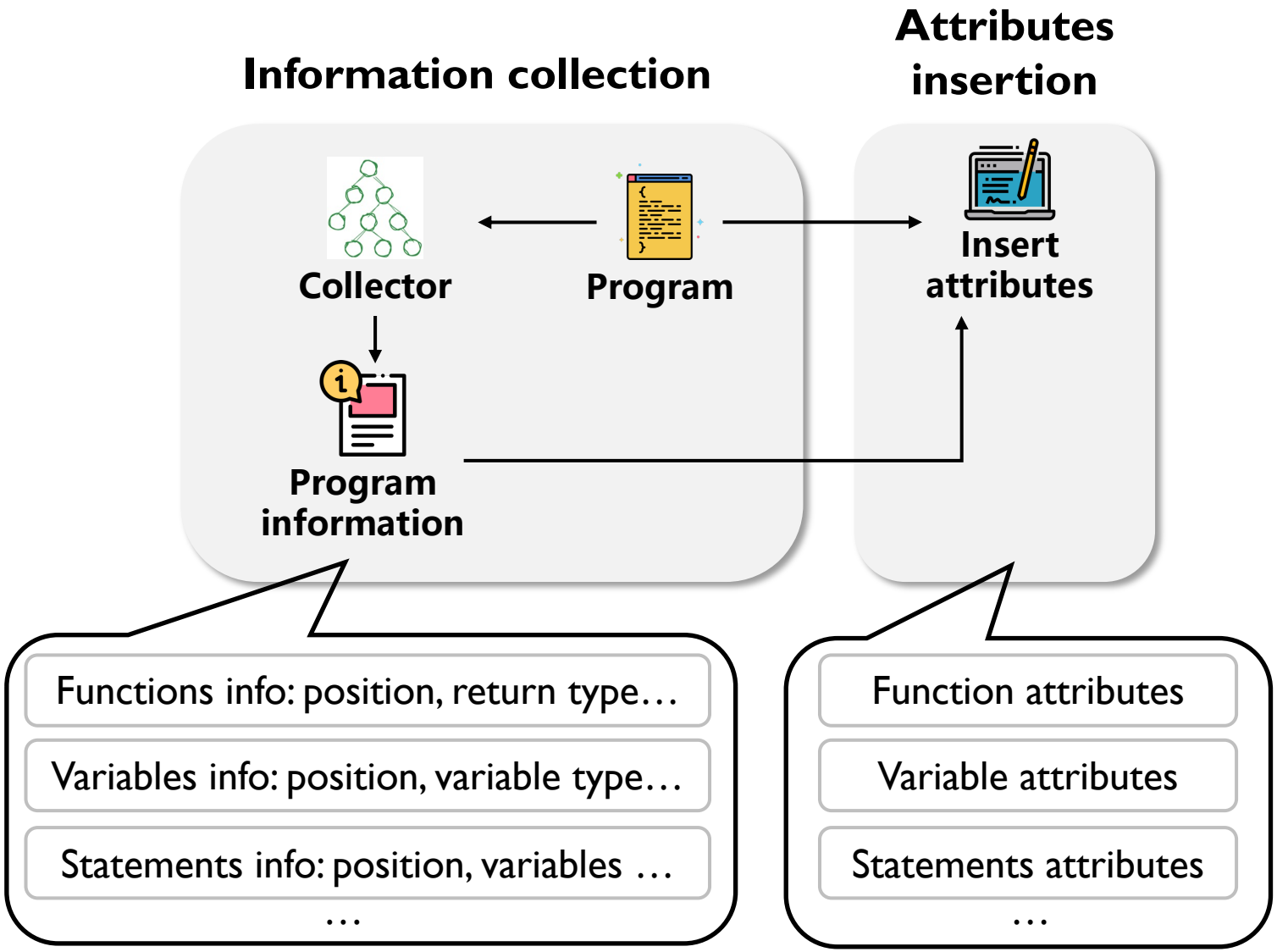
Atlas workflow



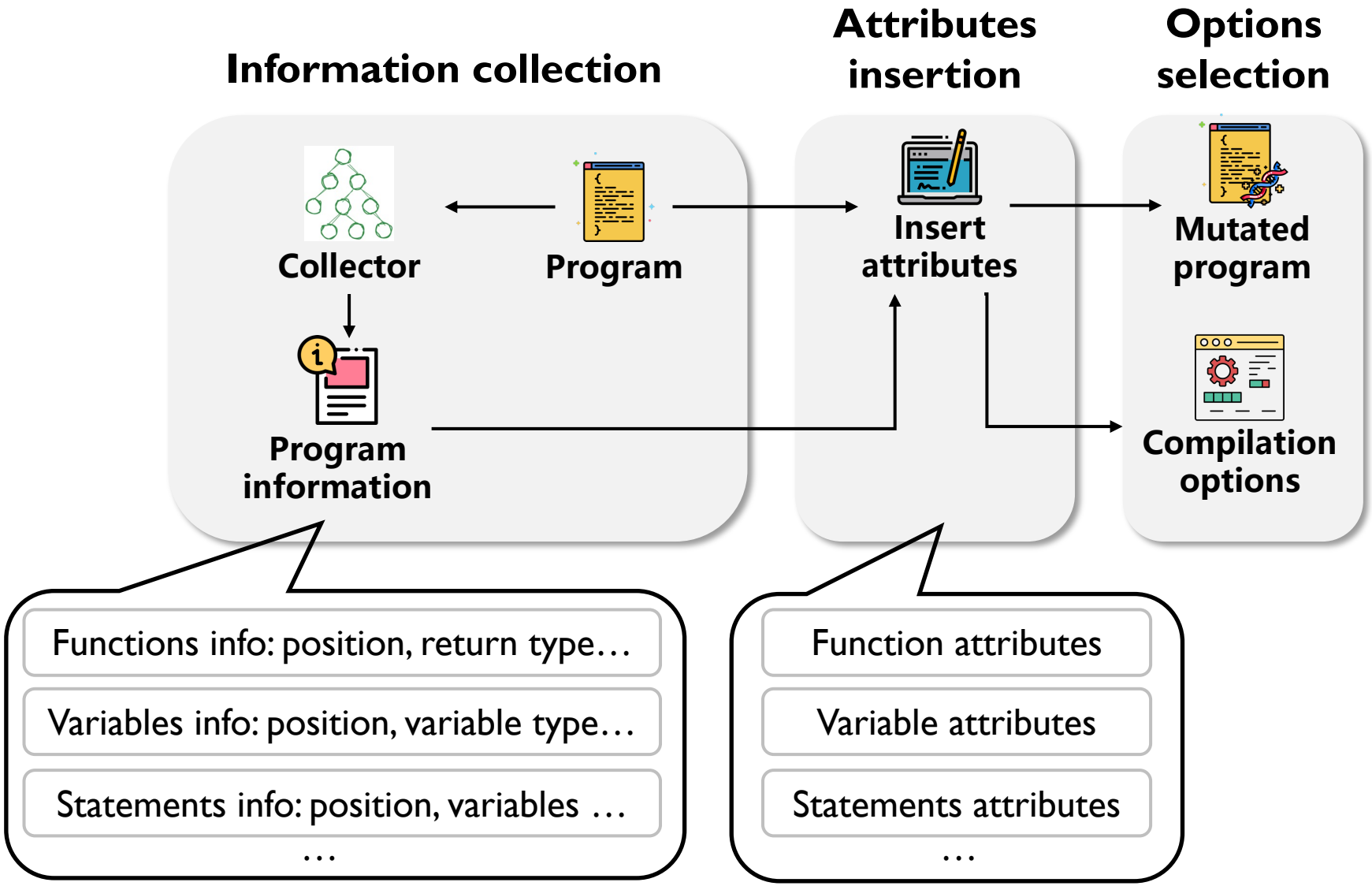
Atlas workflow



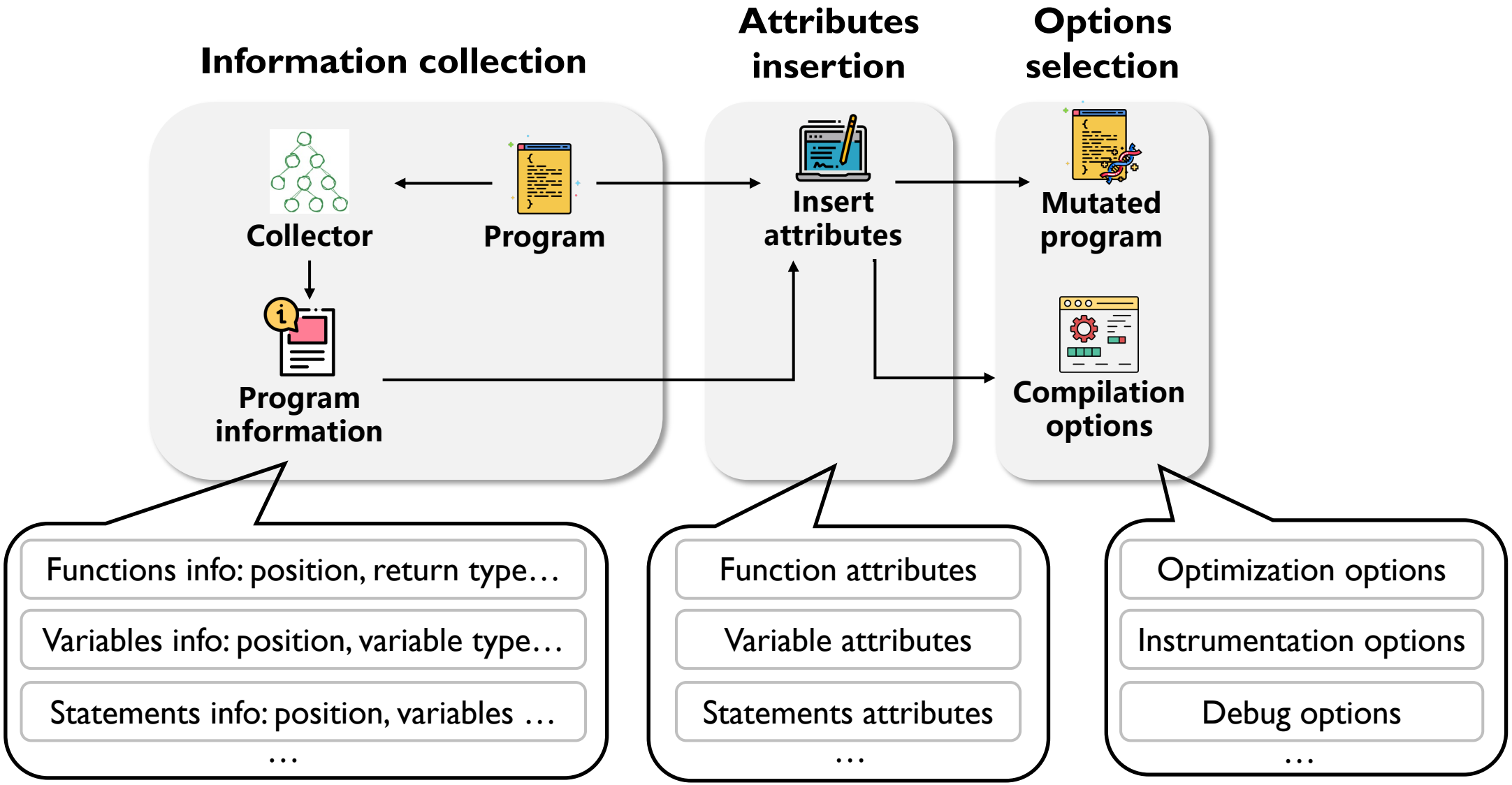
Atlas workflow



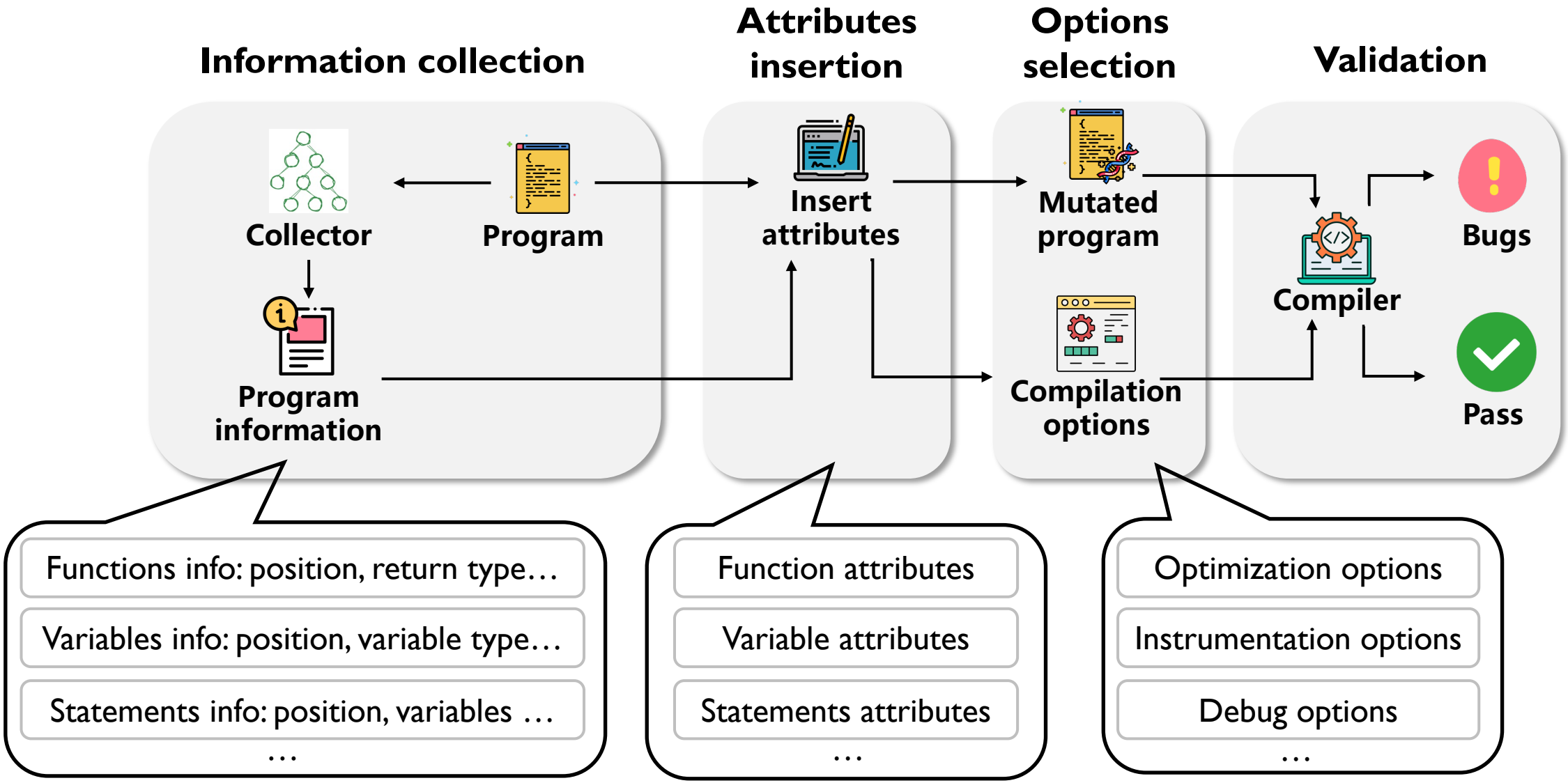
Atlas workflow



Atlas workflow



Atlas workflow



Atlas generated case 1

```
int a;
int b(int);
<func> int c() {
  a = 1;
  while (a)
    a = 2;
  return a;
}
<func> int e(void) {
  int d = c();
  b(d);
}
```

Original Program

Atlas generated case 1

```
int a;
int b(int);
<func> int c() {
  a = 1;
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  return a;
}
<func> int e(void) {
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  b(d);
}
```

Original Program

```
int a;
int b(int);
__attribute__((pure,
  returns_twice))
int c() {
  a = 1;
  while (a)
    a = 2;
  return a;
}
int e(void) {
  int d = c();
  b(d);
}
```

Mutated Program

Atlas generated case 1

```
int a;
int b(int);
<func> int c() {
  a = 1;
  while (a)
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}
<func> int e(void) {
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}
```

Original Program

```
int a;
int b(int);
__attribute__((pure,
  returns_twice))
int c() {
  a = 1;
  while (a)
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  return a;
}
int e(void) {
  int d = c();
  b(d);
}
```

Mutated Program

GCC crashed when compiled it with –O1 –fsanitize=address

https://gcc.gnu.org/bugzilla/show_bug.cgi?id=114687

Atlas generated case 2

```
<var> int a;
void b();
int e(int *c, struct d {
<var> char an[*c]} *) {
  sizeof(struct d);
}
void f() {
  if (e(&a, 0))
    b();
}
```

Original Program

Atlas generated case 2

```
<var> int a;
void b();
int e(int *c, struct d {
<var> char an[*c]} *) {
  sizeof(struct d);
}
void f() {
  if (e(&a, 0))
    b();
}
```

Original Program

```
int a;
void b();
int e(int *c, struct d {
__attribute__((
  vector_size(4)))
  char an[*c]} *) {
  sizeof(struct d);
}
void f() {
  if (e(&a, 0))
    b();
}
```

Mutated Program

Atlas generated case 2

```
<var>  int a;
void b();
int e(int *c, struct d {
<var>  char an[*c]} *) {
  sizeof(struct d);
}
void f() {
  if (e(&a, 0))
    b();
}
```

Original Program

```
int a;
void b();
int e(int *c, struct d {
__attribute__((
  vector_size(4)))
  char an[*c]} *) {
  sizeof(struct d);
}
void f() {
  if (e(&a, 0))
    b();
}
```

GCC Bug 117145

GCC crashed when compiled it with -O2

https://gcc.gnu.org/bugzilla/show_bug.cgi?id=117145

Atlas generated case 3

```
void a (int &x, int &y) {
   <stmt>
   for (i=0; i<10; i++) {
      x += y + 1;
   }
}
```

Original Program

Atlas generated case 3

```
void a (int &x, int &y) {
  <stmt>
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Original Program

```
void a (int &x, int &y) {
  #pragma omp simd
    linear(uval (x): y+1)
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Mutated Program

Atlas generated case 3

```
void a (int &x, int &y) {
  <stmt>
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Original Program

```
void a (int &x, int &y) {
  #pragma omp simd
    linear(uval (x): y+1)
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Mutated Program

Atlas generated case 3

```
void a (int &x, int &y) {
  <stmt>
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Original Program

```
void a (int &x, int &y) {
  #pragma omp simd
    linear(uval (x): y+1)
  for (i=0; i<10; i++) {
    x += y + 1;
  }
}
```

Clang Bug 108166

https://github.com/llvm/llvm-project/issues/108166

Clang crashed when compiled it with –O0

Research Question

- **RQ1: How many compiler bugs have been found by Atlas?**
- **RQ2: How efficient is Atlas in uncovering compiler bugs?**
- **RQ3: Can Atlas improve code coverage?**

RQ1: Effectiveness of Atlas

Reported bugs

	Reported	Confirmed	Fixed
GCC	44	31	13
LLVM	29	27	4
Totl	73	58	17

Distribution of confirmed bugs

Component	GCC	LLVM	Total
Front-End	17	6	23
Middle-End	13	8	21
Optimization	11	5	16
Back-End	3	10	13

✓ 1 GCC P1 bug, 14 GCC P2 bugs

✓ Span a wide range of compiler components

RQ1: Effectiveness of Atlas

Valuable attributes of GCC

Attribute	Type	#	Attribute	Type	#
vector_size	var.	7	alias	func.	1
return_twice	func.	7	no_reorder	func.	1
sanitize	func.	5	noipa	func.	1
simd	func.	4	destructor	func.	1
optimize	func.	4	malloc	func.	1
pure	func.	4	strub	func.	1
const	func.	3	deprecated	func.	1
malloc	func.	2	copy	func.	1
target	func.	2	sentinel	func.	1
aligned	var.	2	nonstring	var.	1
aligned	func.	2	copy	func.	1
flatten	func.	2	always_inline	func.	1
vector_size	func.	2	used	func.	1
constructor	func.	1	interrupt	func.	1

Valuable attributes of LLVM

Attribute	Type	#	Attribute	Type	#
noline	func.	3	speculative	func.	1
vector_size	var.	3	interrupt	func.	1
simd	stat.	2	atomic	func.	1
vectorcall	func.	2	optnone	func.	1
preserve_none	func.	1	nodebug	func.	1
minsize	func.	1	preserve_most	func.	1
sanitize	func.	1	packed	var.	1
opencl	func.	1	regcall	var.	1
loop_vectorize	stmt.	1	target	func.	1
cpu_specific	func.	1	register	func.	1
cold	func.	1	address_space	var.	1
alias	func.	1	constructor	func.	1
noderef	var.	1	-	-	-

Each case contains at least one attribute

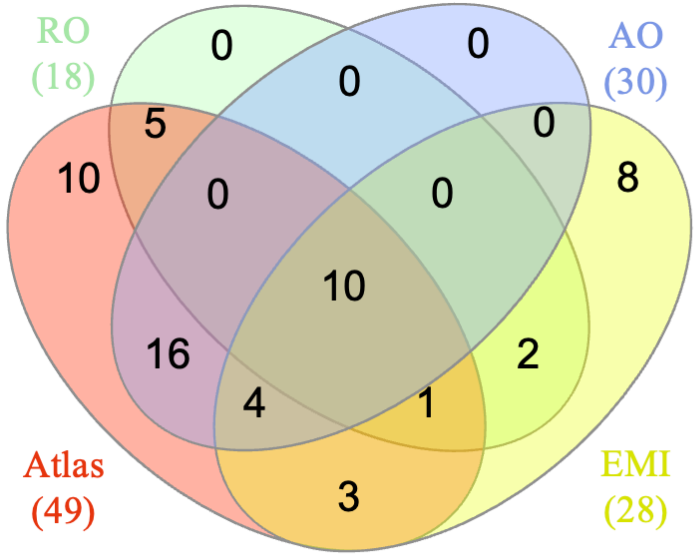
RQ2: Efficiency of Atlas

Detected bugs and generated programs within 10 days

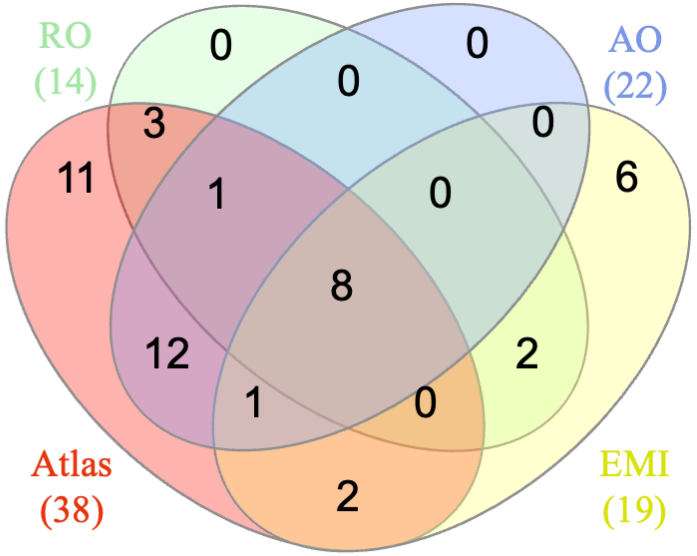
Generators	Techniques	GCC Bugs(#)	LLVM Bugs(#)	Total Bugs(#)	Compilable Programs(#)	Total Programs(#)
Csmith	RO	13	5	18	53,458	53,481
	AO	19	11	30	32,043	47,825
	EMI	17	11	28	48,765	49,279
	ATLAS	32	17	49	30,170	46,416
YARPGen	RO	8	6	14	123,087	123,192
	AO	12	10	22	70,361	108,085
	EMI	10	9	19	101,734	103,628
	ATLAS	25	13	38	62,142	99,439

- ✓ Atlas finds more bugs
- ✓ More than 60% of program generated by Atlas are compliable

RQ2: Efficiency of Atlas



Csmith



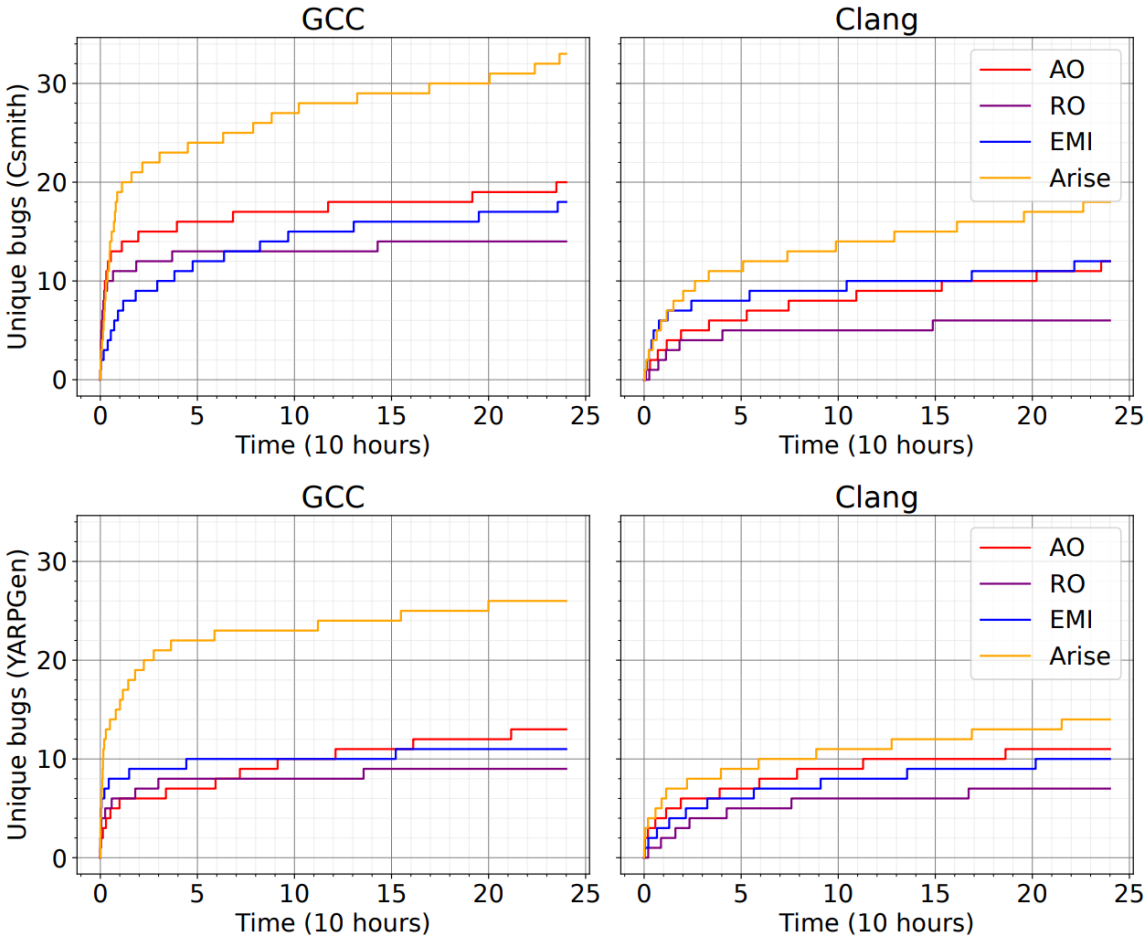
YARPGen

Unique bug found by different approaches

- ✓ **More unique bugs**
- ✓ **109.1% more bugs than other approaches**

RQ2: Efficiency of Atlas

- ✓ **Atlas continues to uncover bugs over a period of 10 days**
- ✓ **Atlas maintains a more consistent discovery rate**



The earliest time each unique bug was discovered

RQ3: Capability of Atlas

Code coverage

Compiler	Techniques	Line	Function	Branch
GCC	RO	33.5%	35.2%	21.1%
	AO	34.7%(+13,080)	36.9%(+419)	22.0%(+10,697)
	EMI	35.3%(+19,619)	36.8%(+314)	22.4%(15,450)
	ATLAS	36.3%(+30,519)	37.6%(+1,152)	23.2%(+24,958)
LLVM	RO	34.4%	25.6%	20.0%
	AO	35.6%(+20,324)	26.5%(+849)	20.9%(+6,472)
	EMI	35.1%(+12,435)	26.9%(+1,307)	21.3%(+9,592)
	ATLAS	36.8%(+41,806)	27.6%(+1,953)	21.7%(+12,954)

- ✓ **Atlas achieves the highest code coverage in all metrics**
- ✓ **Atlas brings the largest improvements**

Conclusion

- **Target**: achieve fine-grained control over compilation for compiler testing
- **Our solution**:
  - ✓ Insert attribute into code target specific elements such as functions, variables, and statements
  - ✓ Combine various options that activate the attributes during compilation
- **Take away**: attributes enable precise control over the compilation strategies applied to individual code elements

Thank You !