CryptOpt: Verified Compilation with Randomized Program Search for Cryptographic Primitives

Chitchanok Chuengsatiansup

The University of Melbourne, Australia

ACAI Workshop 2023

About Me

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2010	**Research Student:** The University of Tokyo, Japan
2006	**Bachelor's Student:** Chulalongkorn University, Thailand

Efficient and Secure Cryptosystems

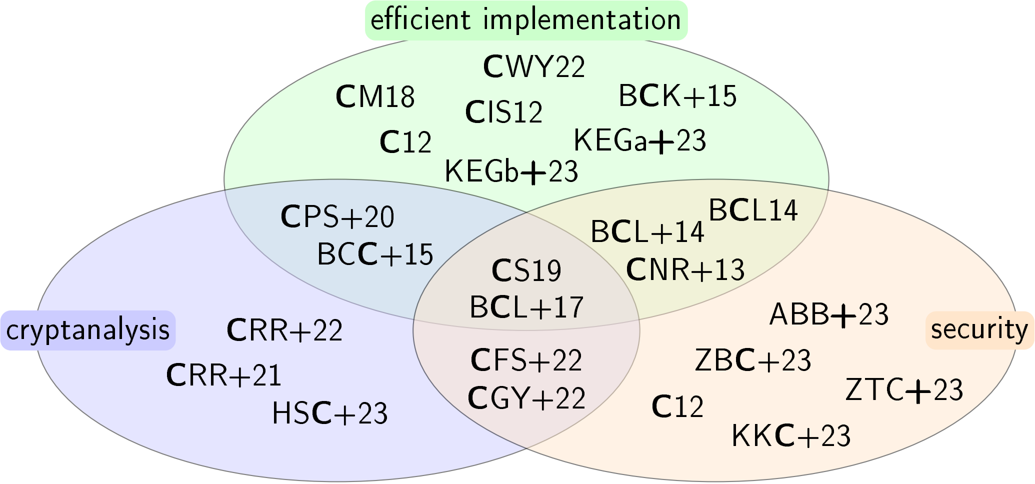
Efficient and Secure Cryptosystems

efficient implementation

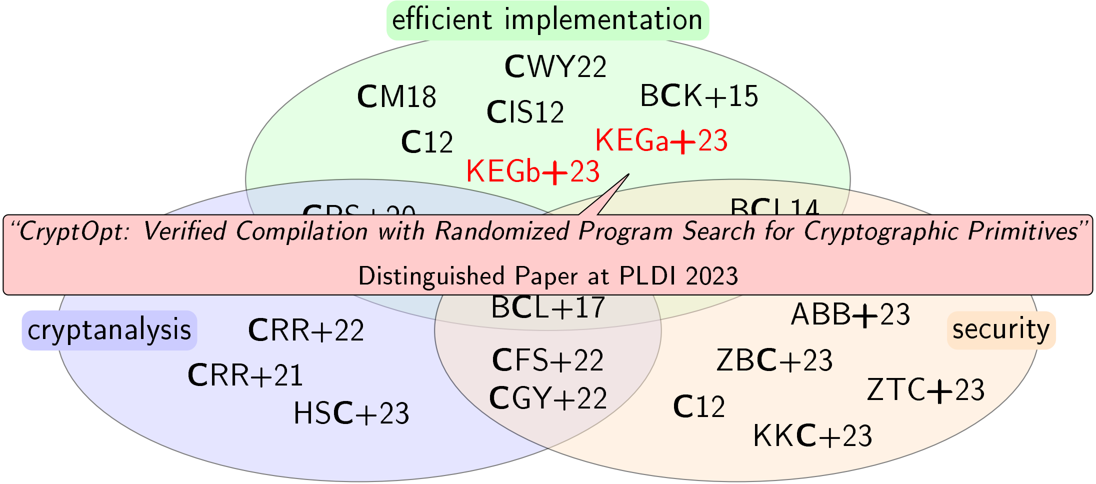
cryptanalysis

security

Efficient and Secure Cryptosystems



Efficient and Secure Cryptosystems



Efficient and Secure Cryptosystems

efficient implementation

CWY22

CM18

CIS12

BCK+15

C12

KEGa+23

KEGb+23

"CryptOpt: Verified Compilation with Randomized Program Search for Cryptographic Primitives"

Distinguished Paper at PLDI 2023

Motivation

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- Correct: produce expected output

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- Efficient: high-speed high-security

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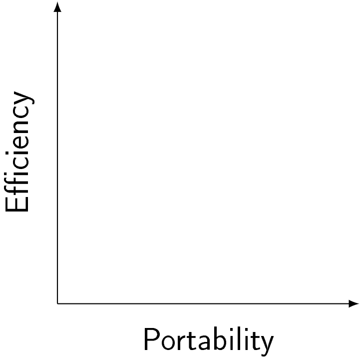

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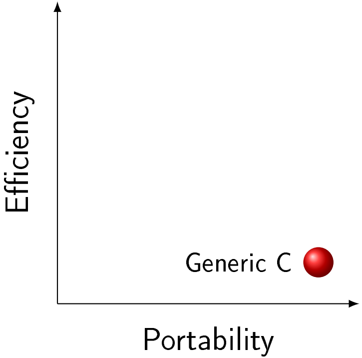

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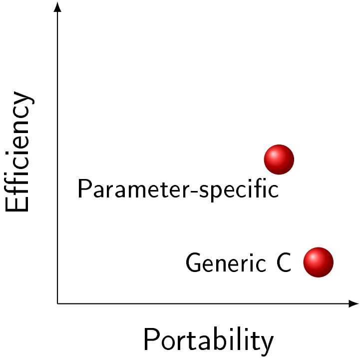

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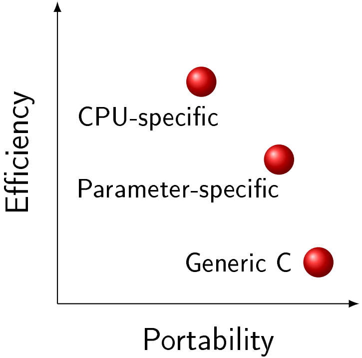

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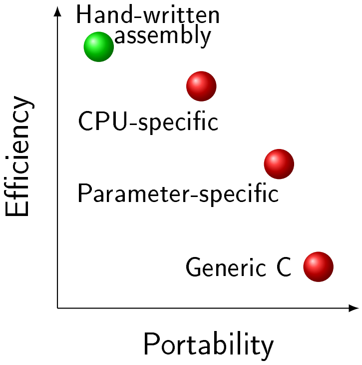

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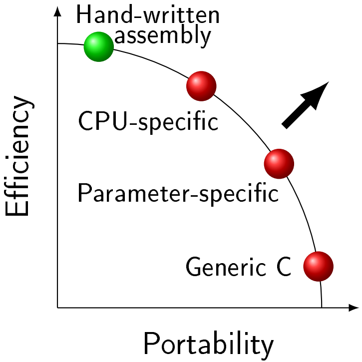

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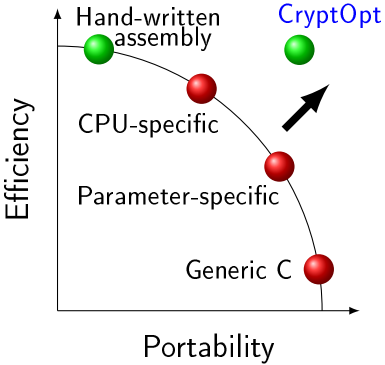

Observation

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- Compilers are general-purpose

Observation

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- Cryptographic code has “special” structures

Constant-Time Programming

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- No *secret-dependent* control flow

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- No *secret-dependent* memory access

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Constant-Time Programming

- No *secret-dependent* control flow
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- No *secret-dependent* variable-time instruction
  - CryptOpt: constant-time instruction

Optimization Strategies

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Optimization Strategies

- Straight-line code in static single assignment (SSA)
  - ensure constant-time code
- Combinatorial optimization
  - search for best-performing implementation
- Random local search (RLS) with bet-and-run heuristic
  - "bet" explores up to budget then "run" continues from the best

Search for Fast Implementation

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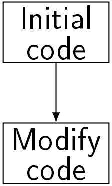
Initial code

Search for Fast Implementation



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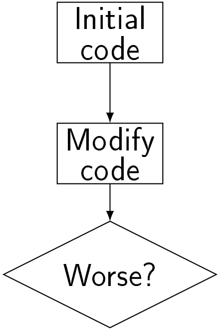

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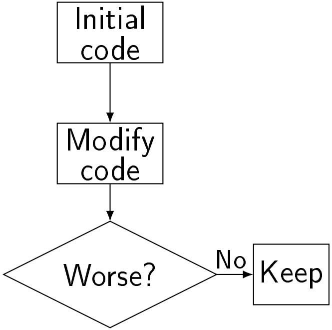

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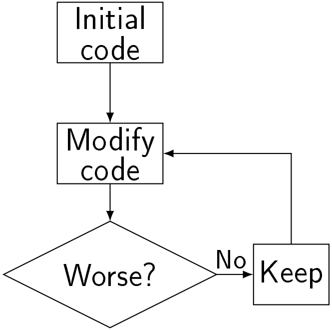

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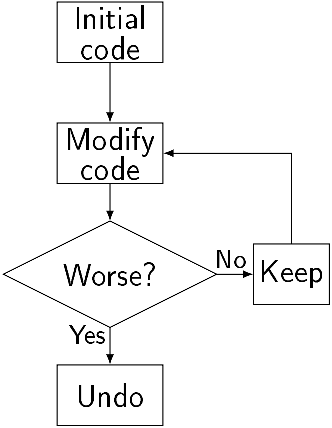

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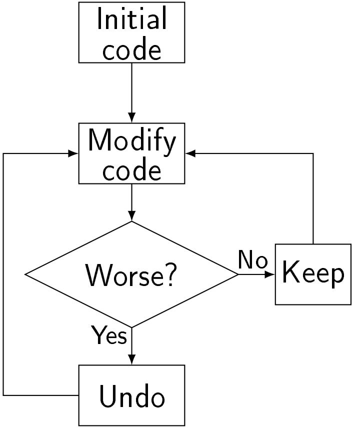

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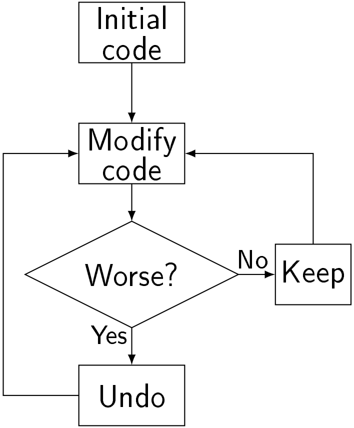
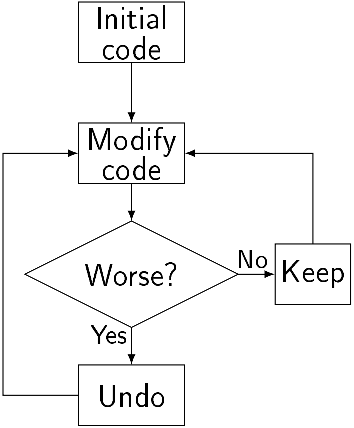


Random Local Search

Search for Fast Implementation



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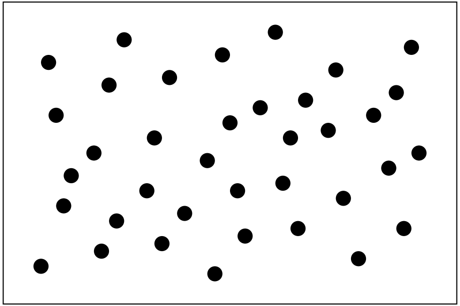

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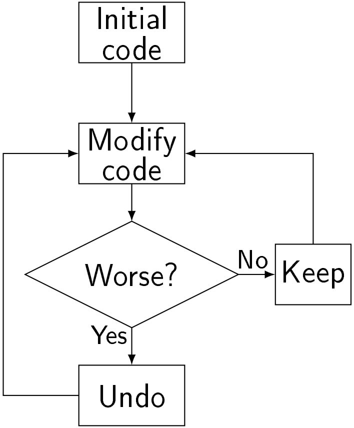

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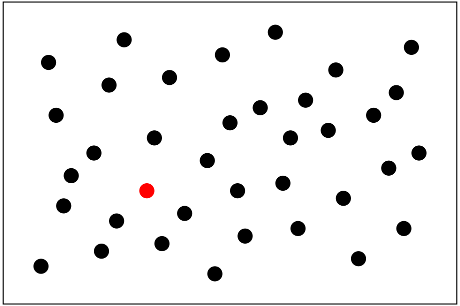

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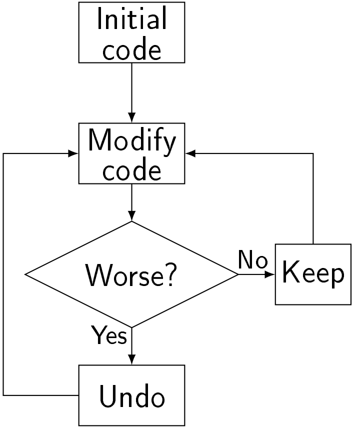

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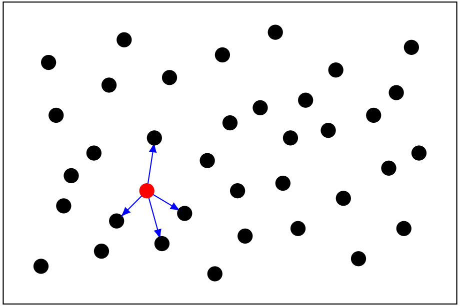

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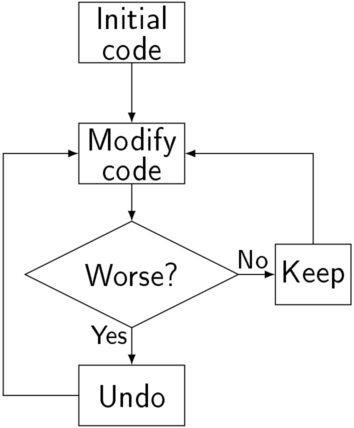

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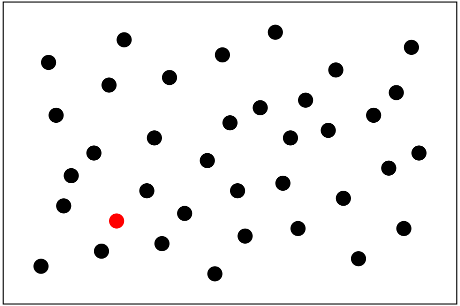

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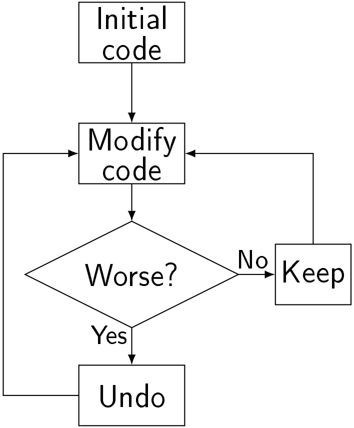

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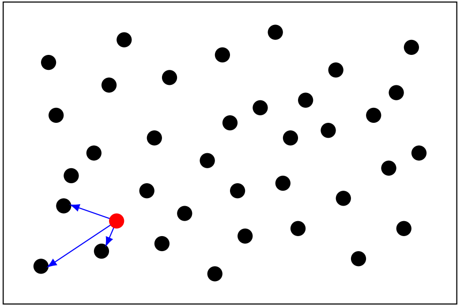

Example Function: $(X + Y) \cdot Z + Z^2$

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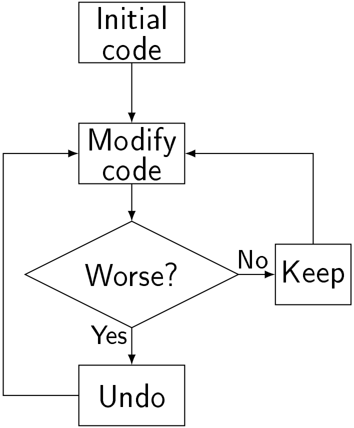

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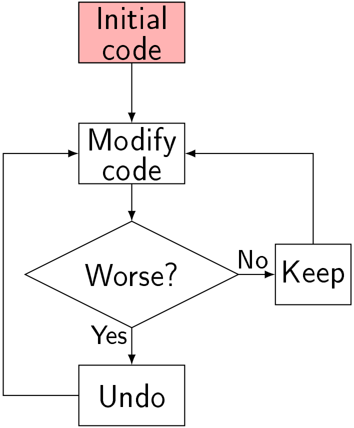

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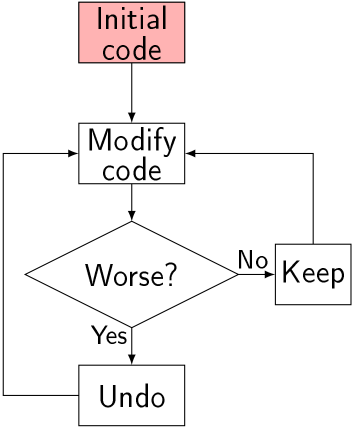

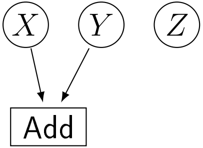

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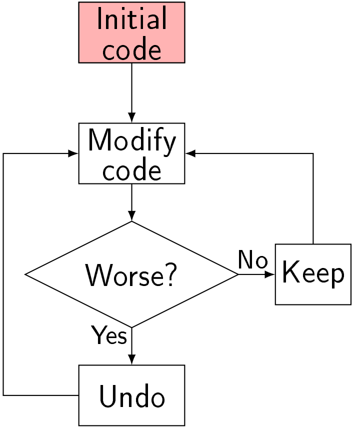

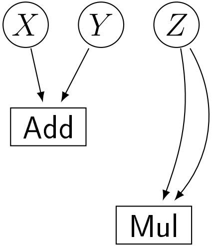

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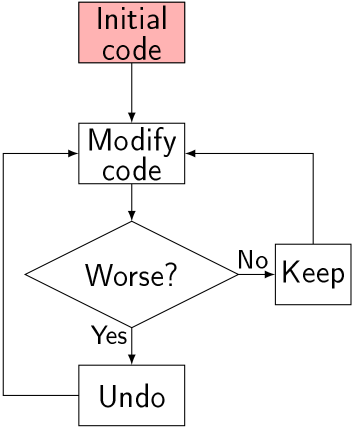

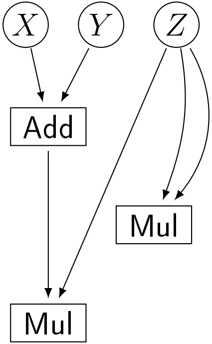

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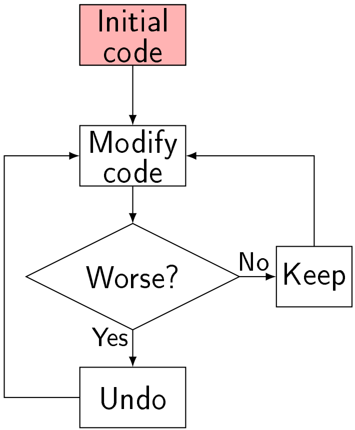

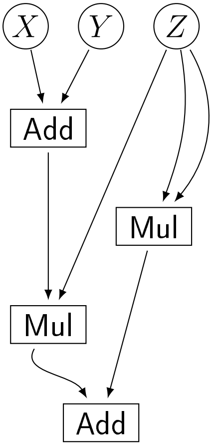

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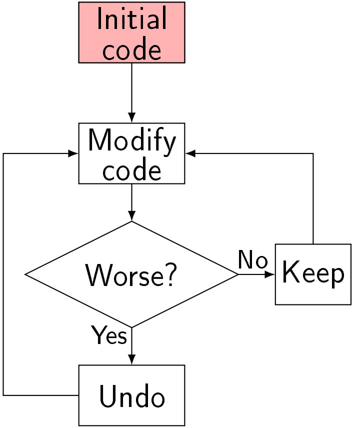

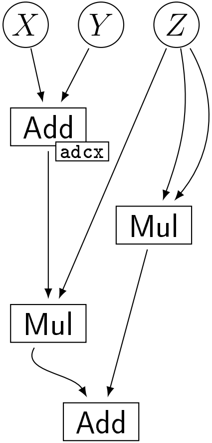


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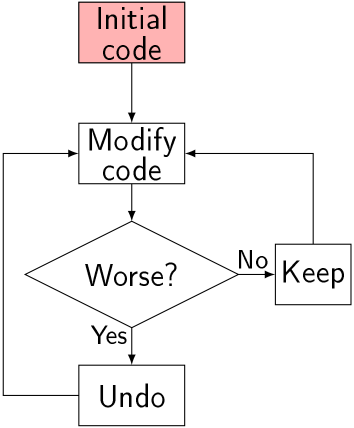

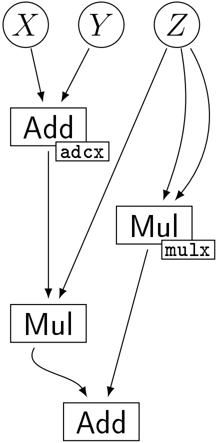


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mov rax, [X]
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mov rdx, [Z]
mulx r8, r9, rax
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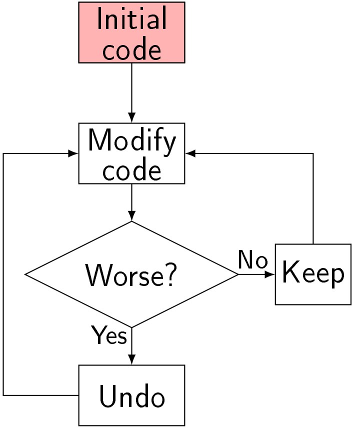

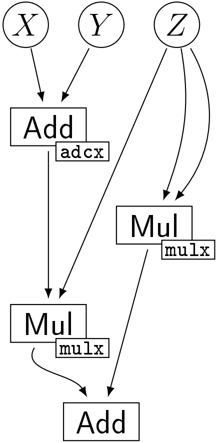


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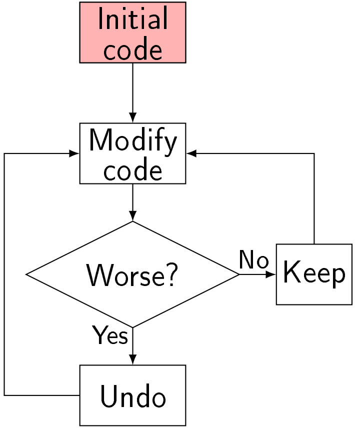

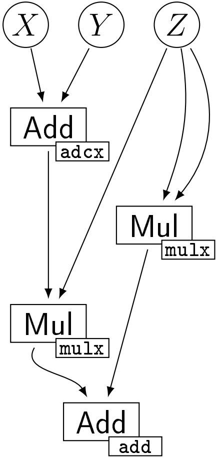


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mov rdx, [Z]
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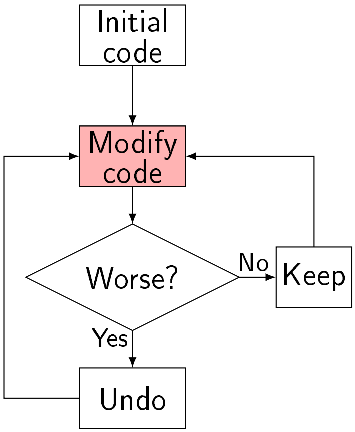
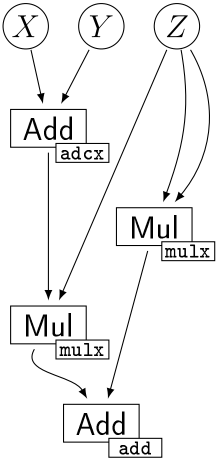
mulx r10, r11, [Z]

add r11, r9
mov [out], r11
```

Example Function: $(X+Y)\cdot Z + Z^2$



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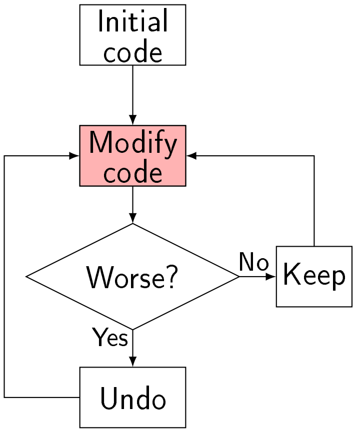

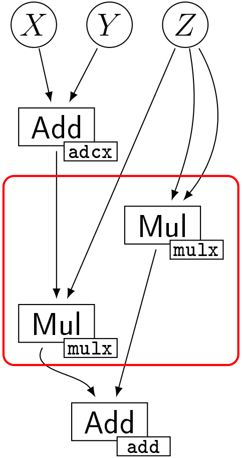


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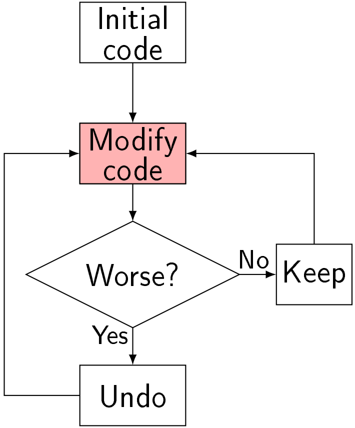
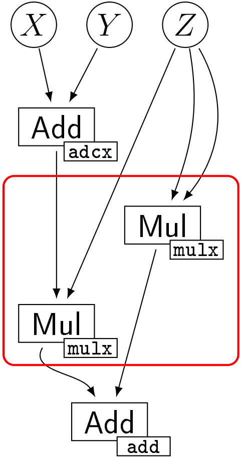
Example Function: $(X + Y) \cdot Z + Z^2$



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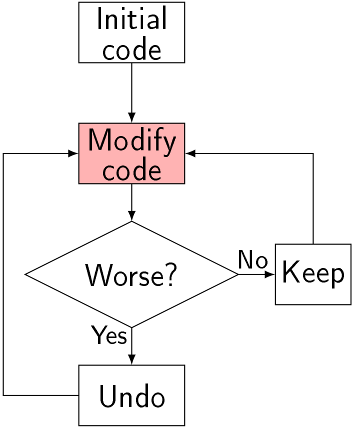
clc
adcx rax, [Y]

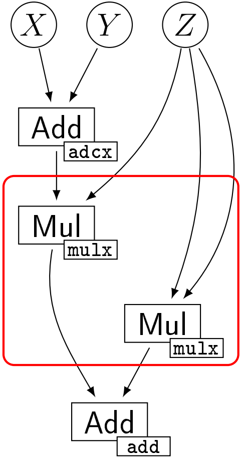
mov rdx, [Z]
mulx r8, r9, rax


mulx r10, r11, [Z]


add r11, r9
mov [out], r11
```

Example Function: $(X + Y) \cdot Z + Z^2$ [reorder]





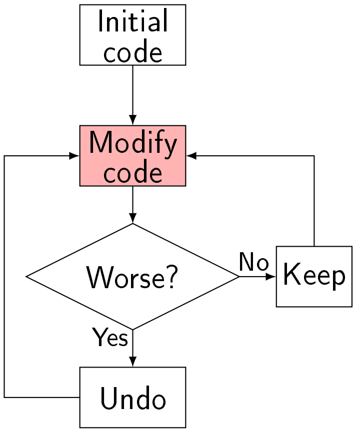

```
mov rax, [X]
clc
adcx rax, [Y]

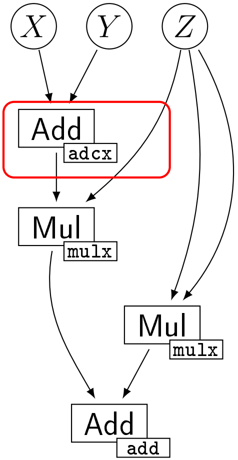
mov rdx, [Z]
mulx r10, r11, [Z]


mulx r8, r9, rax


add r11, r9
mov [out], r11
```

Example Function: $(X + Y) \cdot Z + Z^2$ [template]



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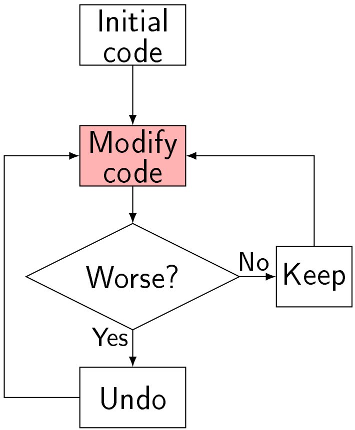
mov rax, [X]
clc
adcx rax, [Y]

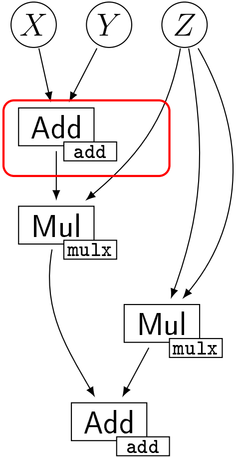
mov rdx, [Z]
mulx r10, r11, [Z]

mulx r8, r9, rax

add r11, r9
mov [out], r11
```

Example Function: $(X + Y) \cdot Z + Z^2$ [template]





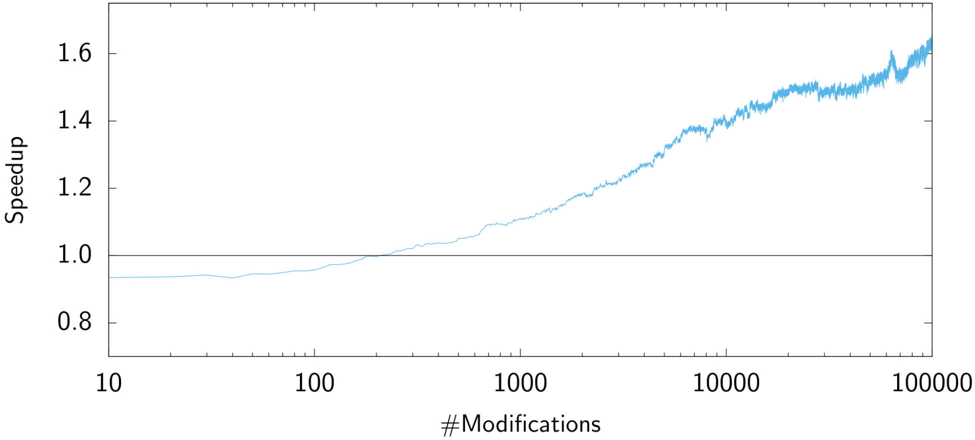

```
mov rax, [X]
clc
add rax, [Y]

mov rdx, [Z]
mulx r10, r11, [Z]

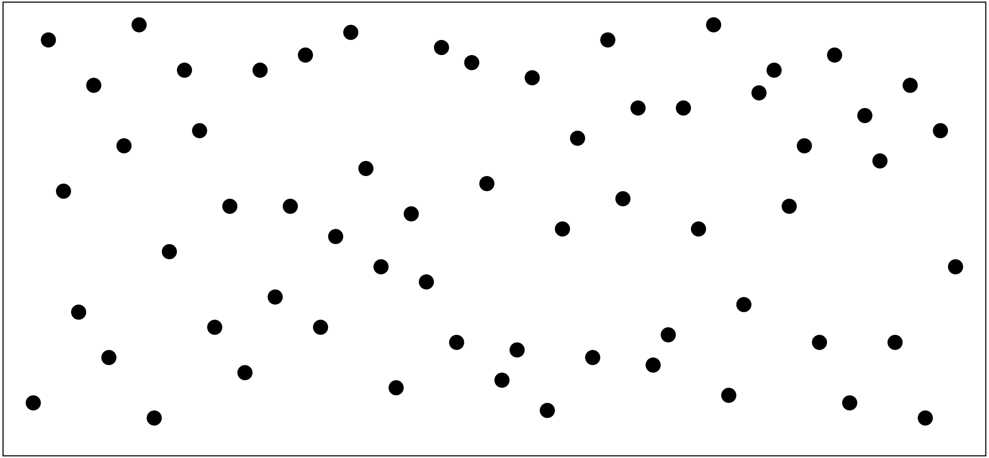
mulx r8, r9, rax

add r11, r9
mov [out], r11
```

Optimization Progress



Random Local Search with Bet-and-Run



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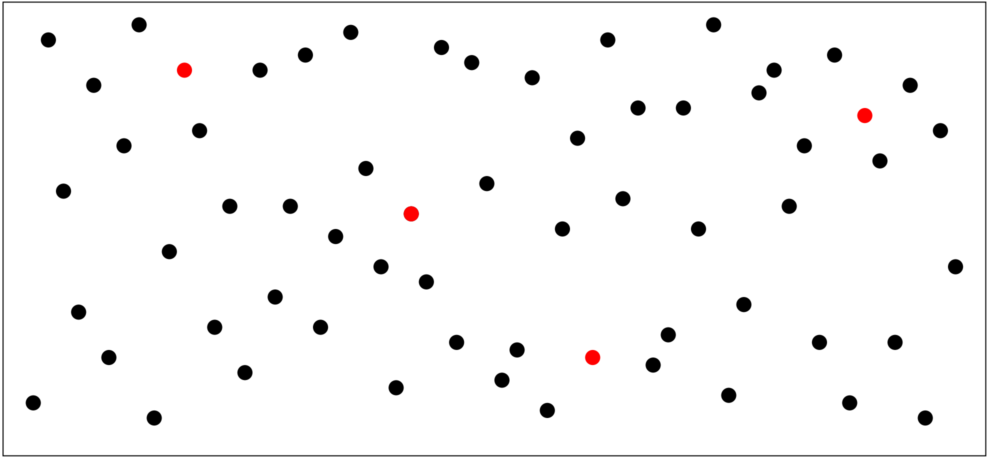
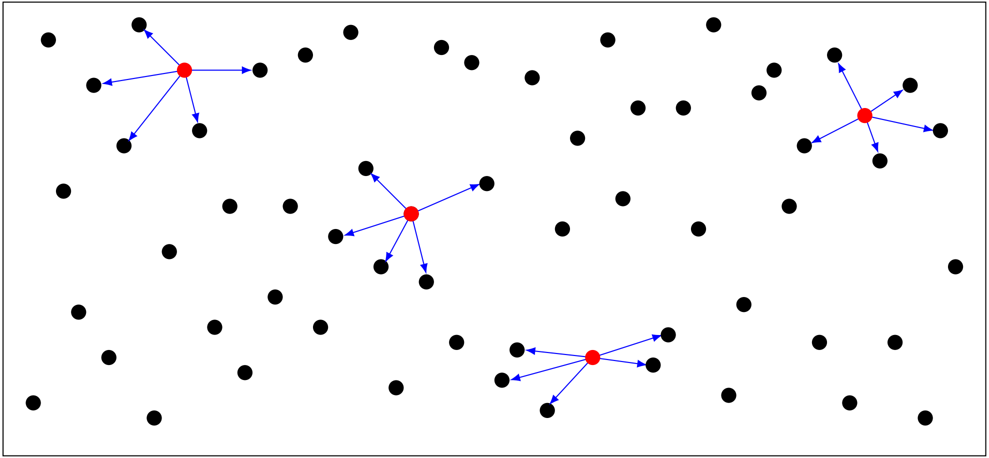
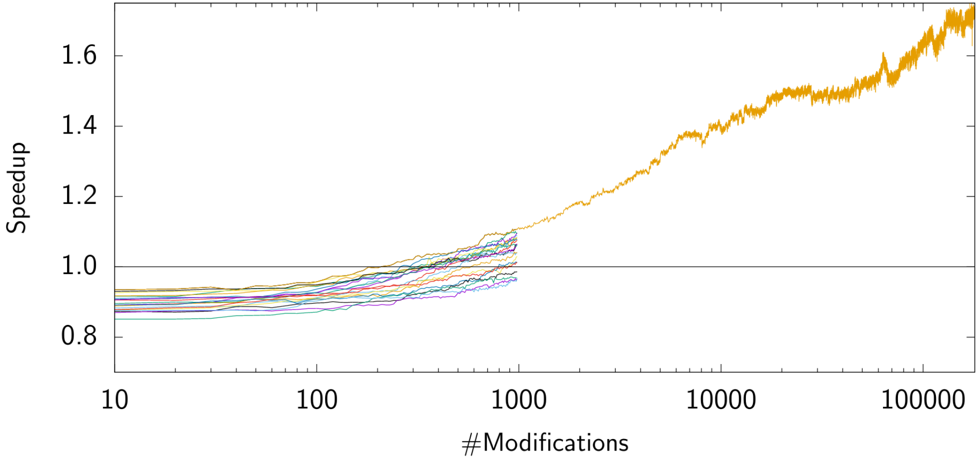


Random Local Search with Bet-and-Run



Bet-and-Run in Action



Fiat Cryptography

Fiat Cryptography
Erbsen et al.
IEEE S&P 2019

Fiat Cryptography

Functional
program

↓

Fiat Cryptography
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↓

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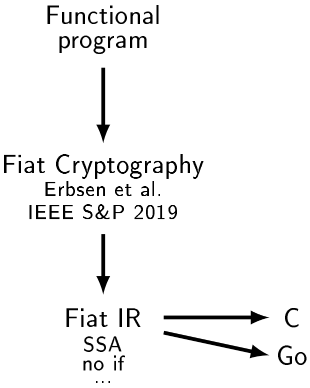
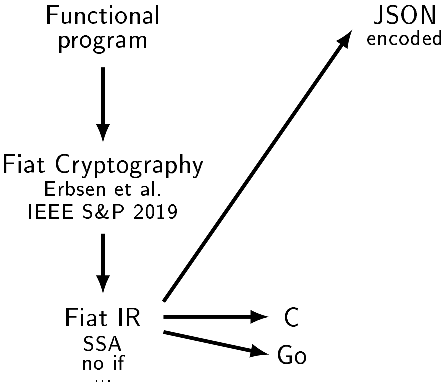
↓

Fiat IR
SSA
no if
...

Fiat Cryptography



Fiat Cryptography



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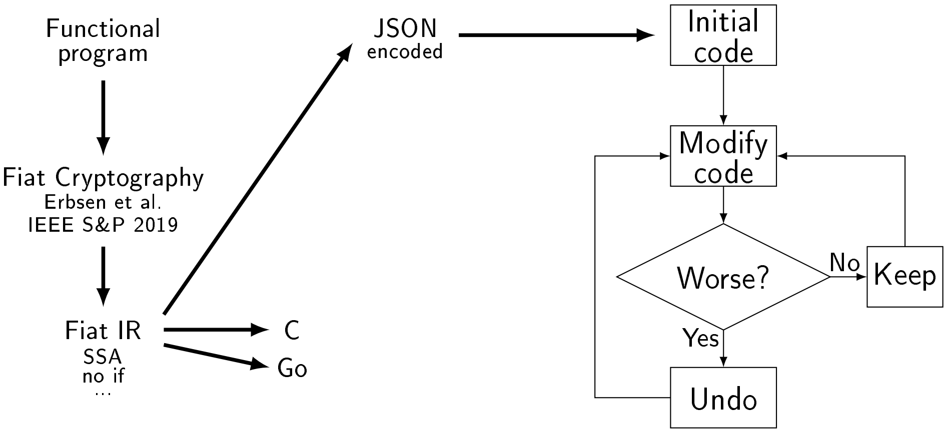
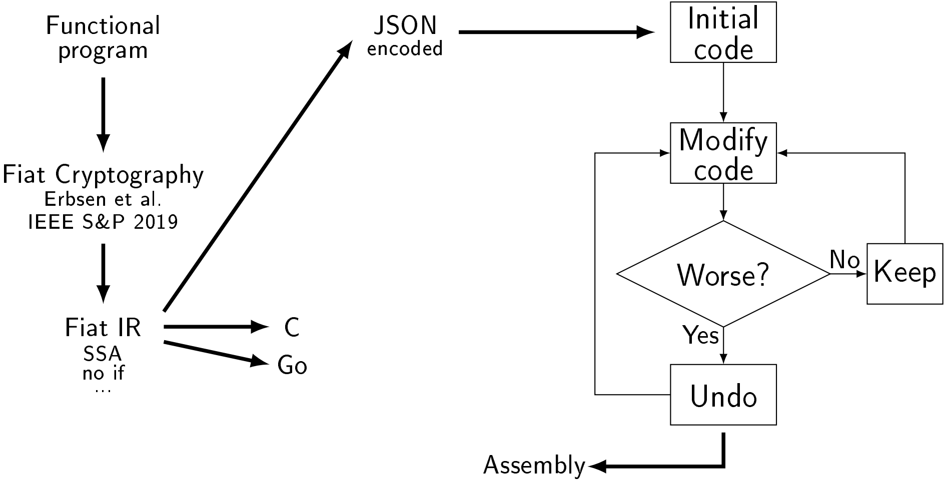


Fiat Cryptography



Performance: Field Arithmetic

Geometric Mean (4x AMD, 6x Intel)

	Multiply		Square	
Curve	Clang	GCC	Clang	GCC
Curve25519				
P-224				
P-256				
P-384				
SIKEp434				
Curve448				
P-521				
Poly1305				
secp256k1				

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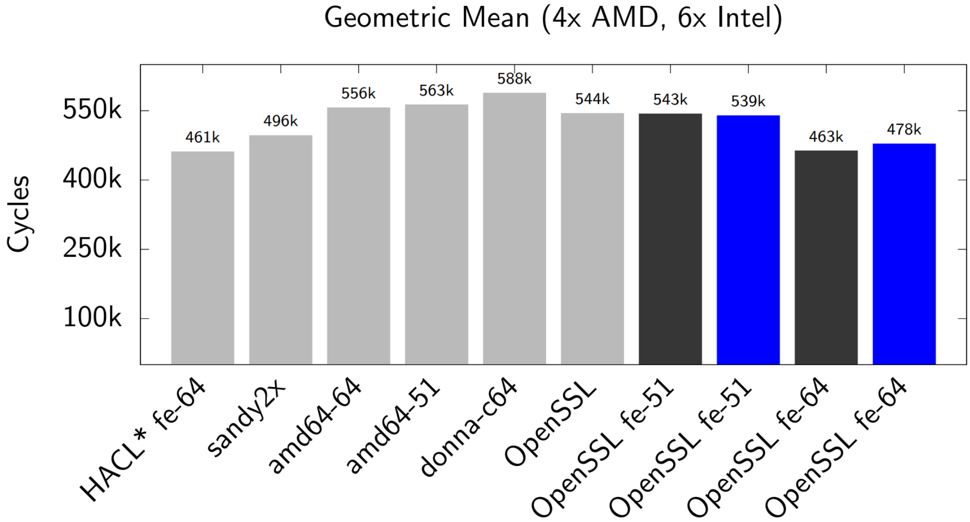
	Multiply		Square	
Curve	Clang	GCC	Clang	GCC
Curve25519	1.19	1.14	1.14	1.18
P-224				
P-256				
P-384				
SIKEp434				
Curve448				
P-521				
Poly1305				
secp256k1				

Performance: Field Arithmetic

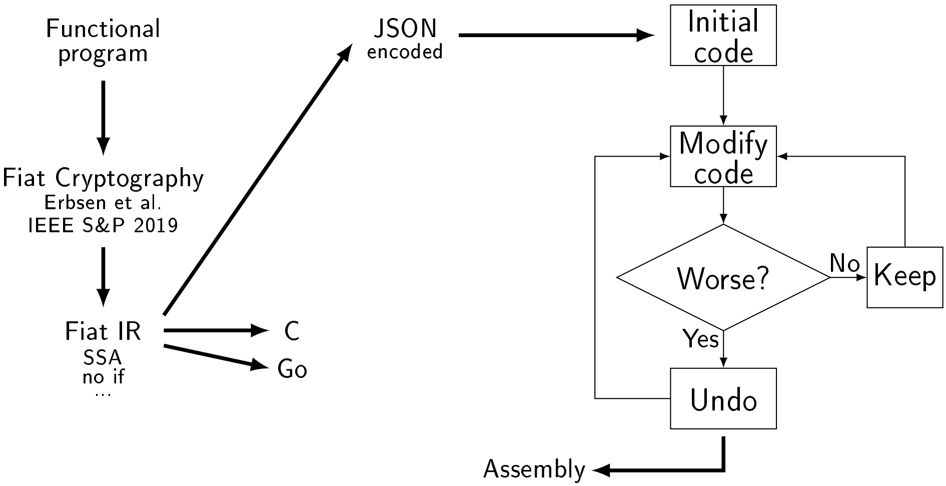
Geometric Mean (4x AMD, 6x Intel)

	Multiply		Square	
Curve	Clang	GCC	Clang	GCC
Curve25519	1.19	1.14	1.14	1.18
P-224	1.31	1.87	1.24	1.84
P-256	1.27	1.79	1.30	1.85
P-384	1.12	1.66	1.08	1.60
SIKEp434	1.30	1.70	1.29	1.83
Curve448	1.02	0.95	1.00	0.99
P-521	1.20	1.06	1.25	1.11
Poly1305	1.10	1.15	1.09	1.16
secp256k1	1.34	1.73	1.32	1.74

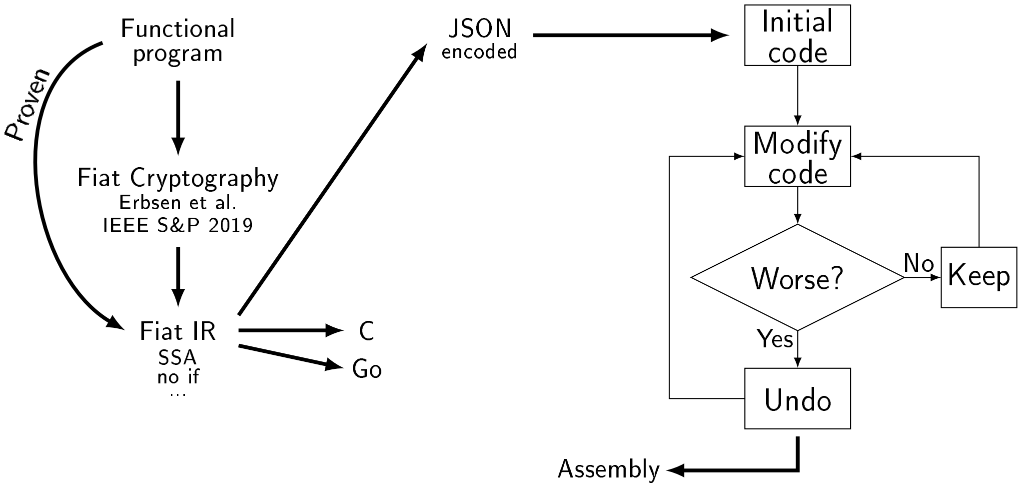
Performance: Scalar Multiplication



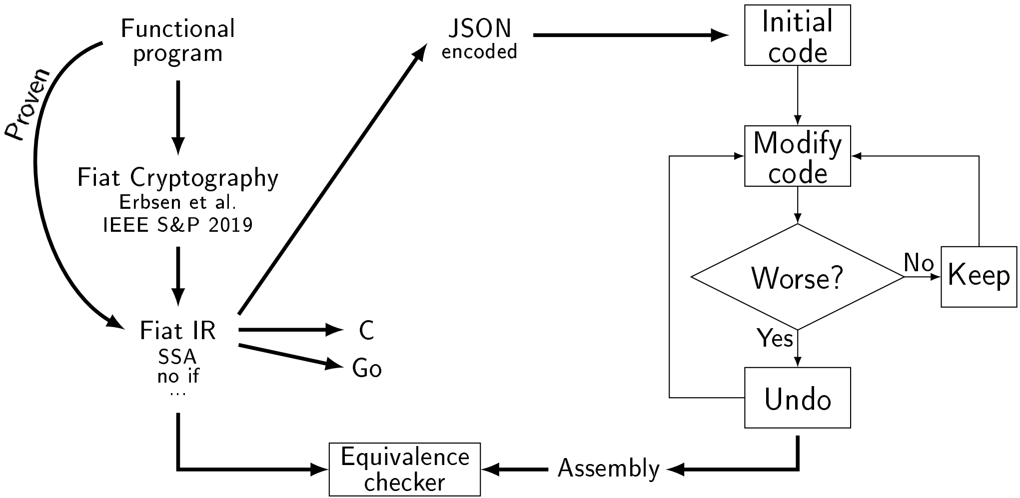
Correctness



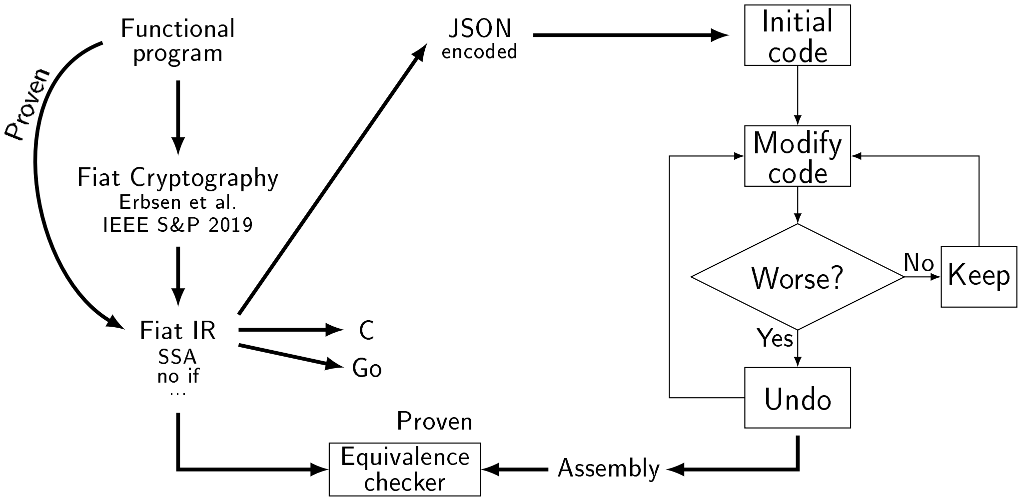
Correctness



Correctness



Correctness



Achievements

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- CryptOpt: automatic cryptographic code optimizer

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- https://0xade1a1de.github.io/CryptOpt

GitHub Project