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

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The University of Melbourne, Australia

Future Communications Workshop

Joint work with A. Chlipala, O. Conoly, A. Erbsen, D. Genkin, J. Gross, J. Kuepper, C. Sun, S. Tian, M. Wagner, D. Wu and Y. Yarom





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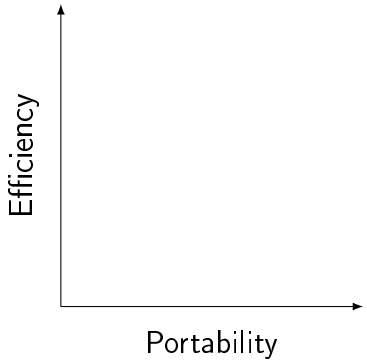

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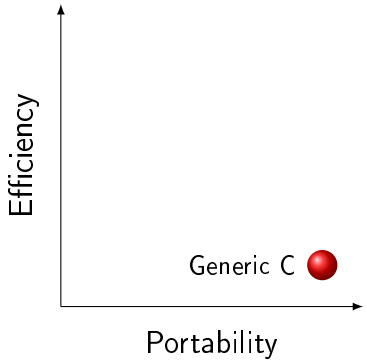

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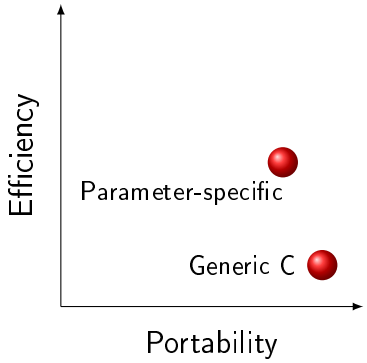

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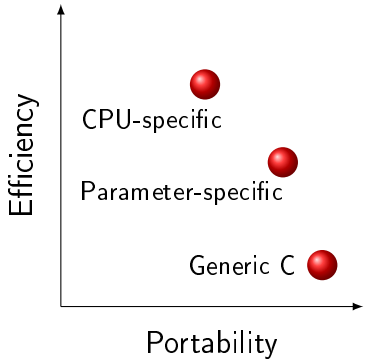

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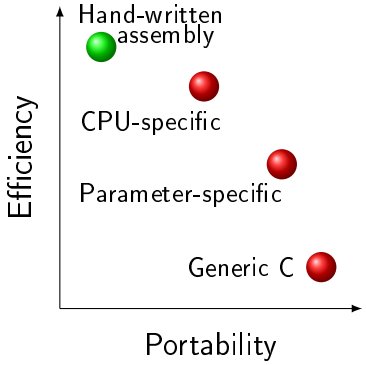

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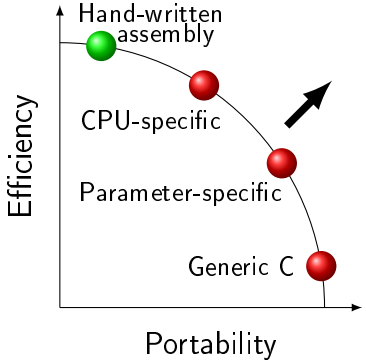

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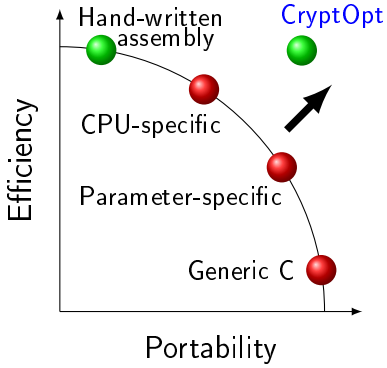

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- Cryptographic code has “special” structures

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  - CryptOpt: constant-time instruction

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- 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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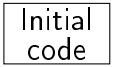

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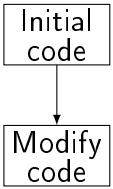

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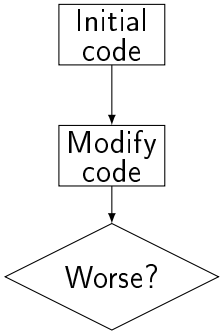

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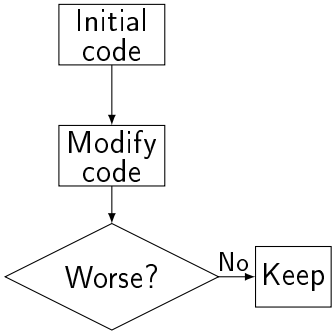

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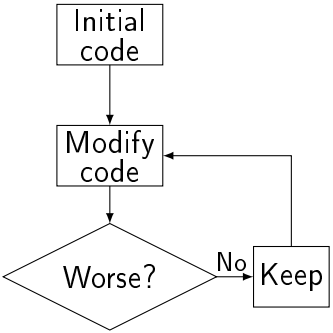

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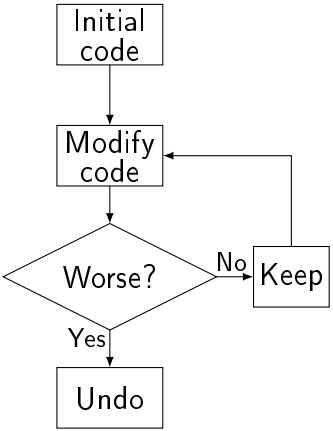

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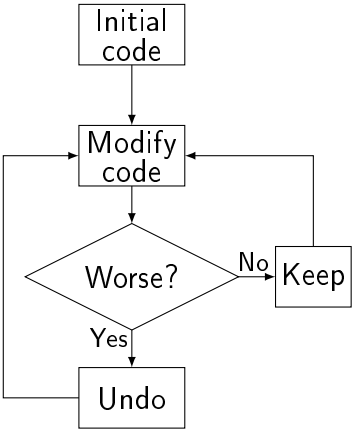

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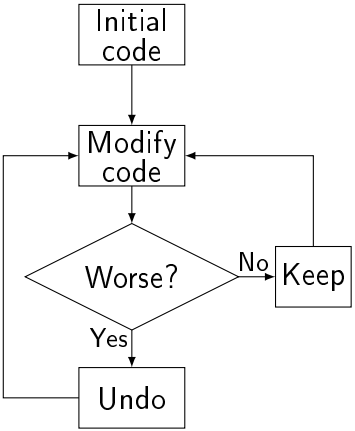


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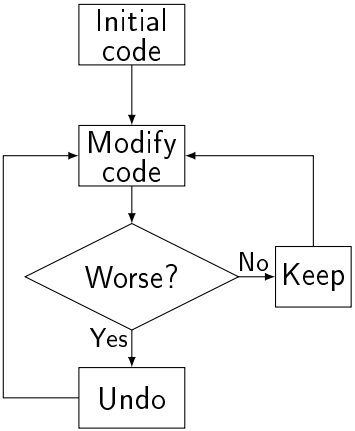


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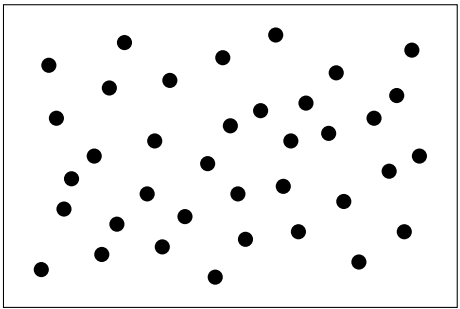

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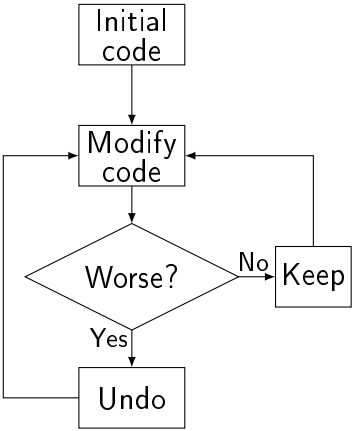


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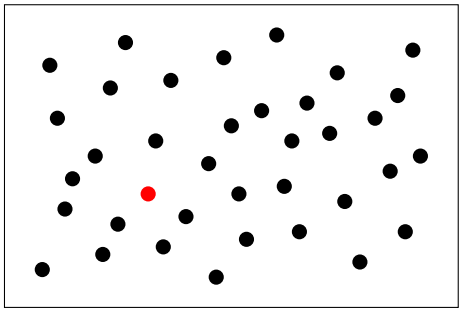

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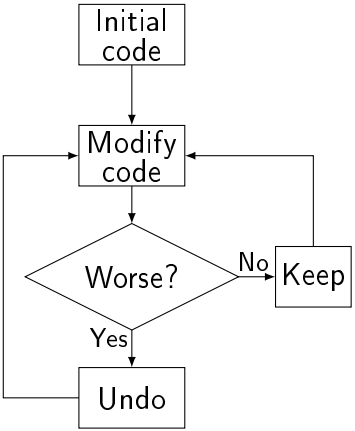


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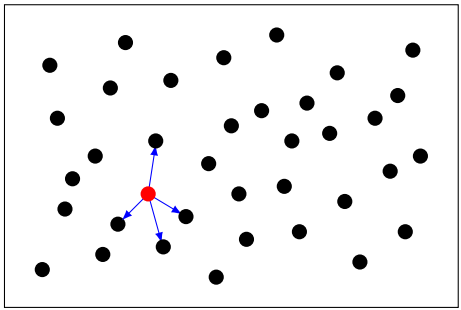

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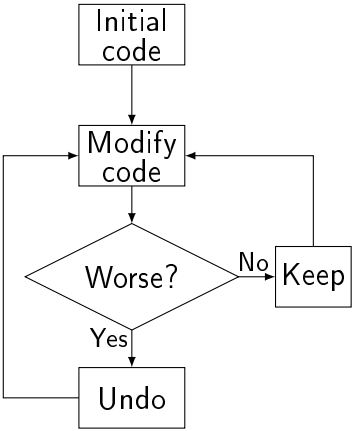


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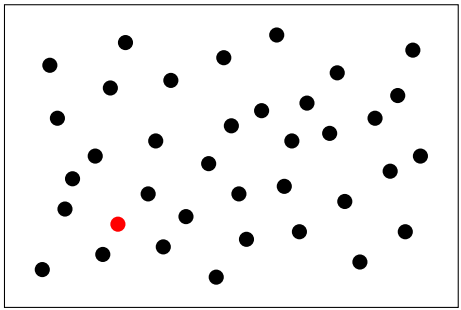

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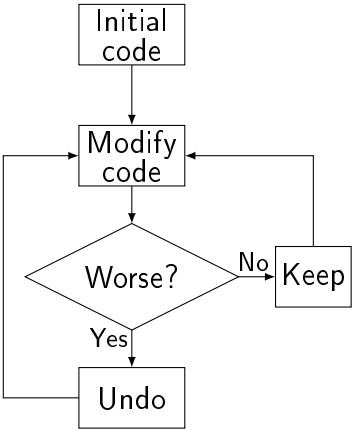


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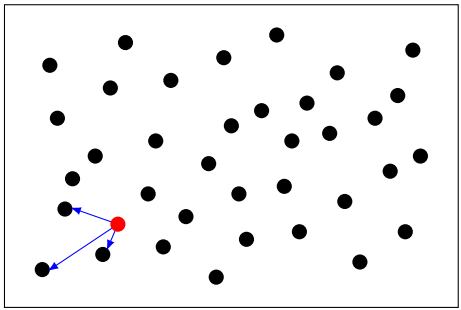

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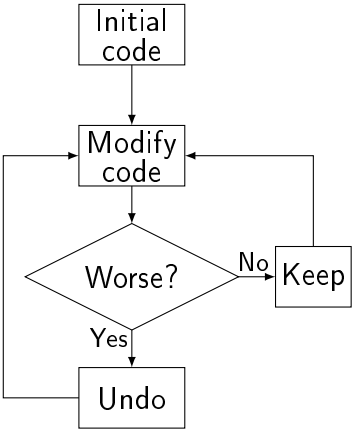

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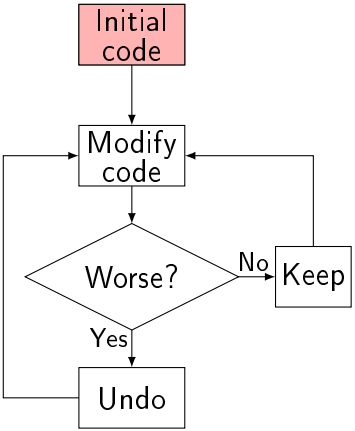


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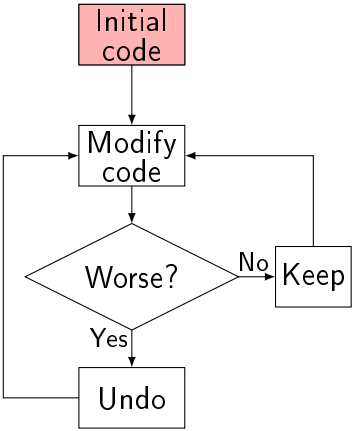


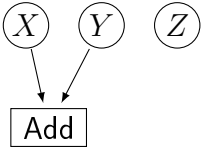

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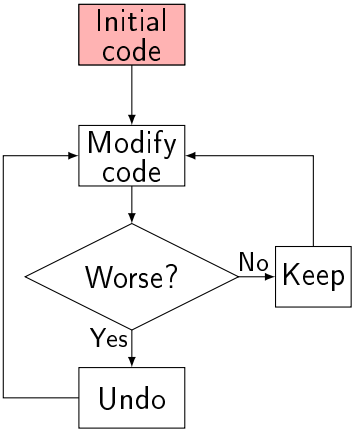


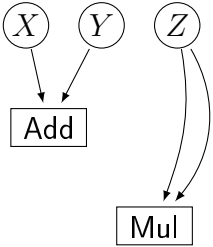

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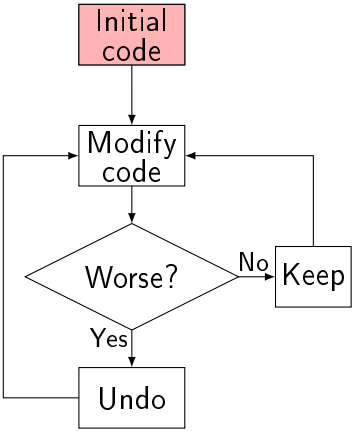


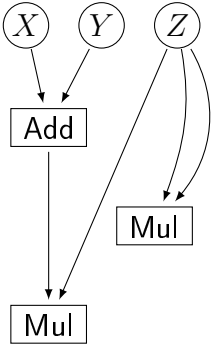

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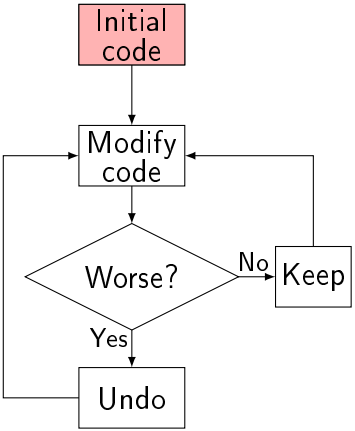


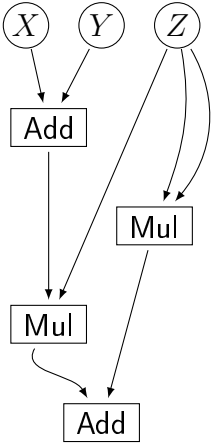

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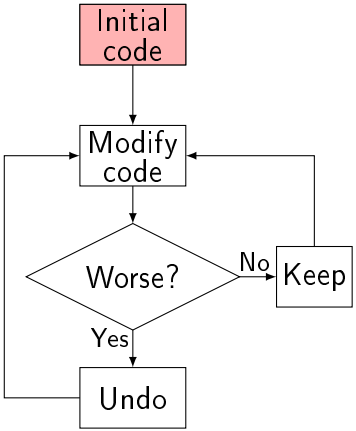


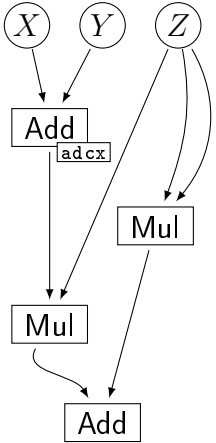


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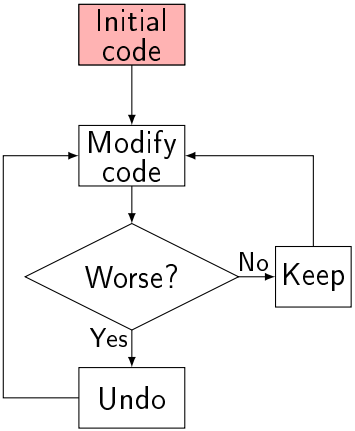


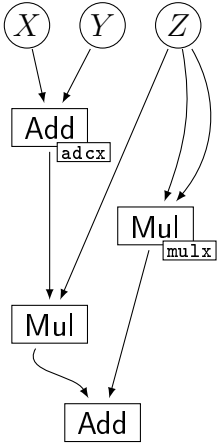


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mov rdx, [Z]
mulx r8, r9, rax
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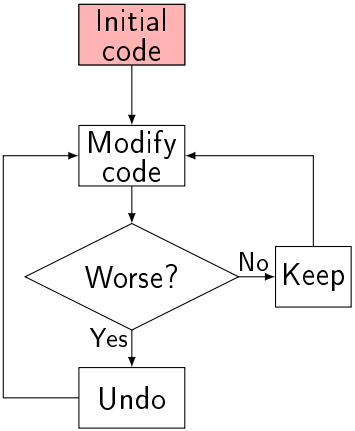


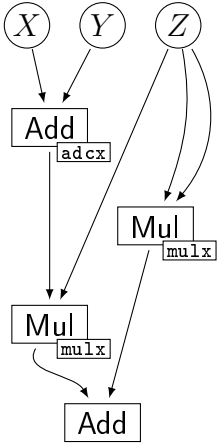


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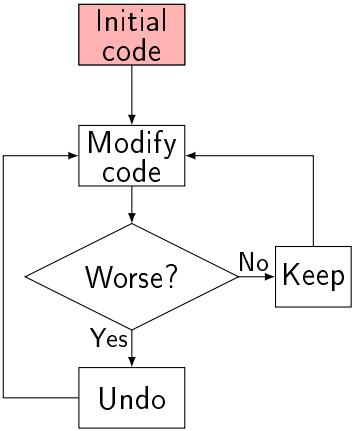


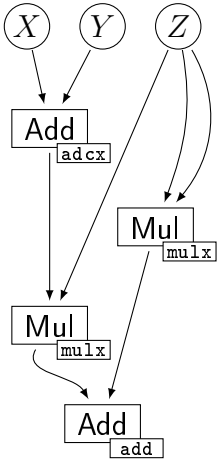


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mov rdx, [Z]
mulx r8, r9, rax

mulx r10, r11, [Z]

add r11, r9
mov [out], r11
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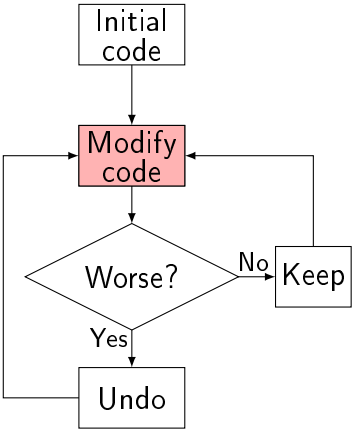


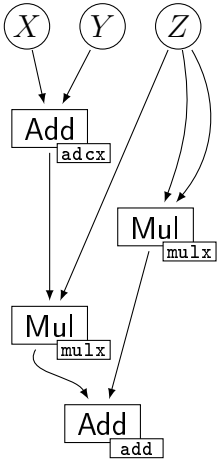


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mov rdx, [Z]
mulx r8, r9, rax

mulx r10, r11, [Z]

add r11, r9
mov [out], r11
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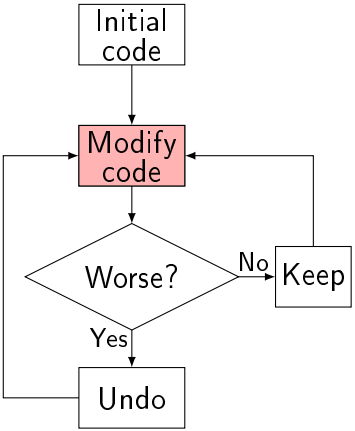


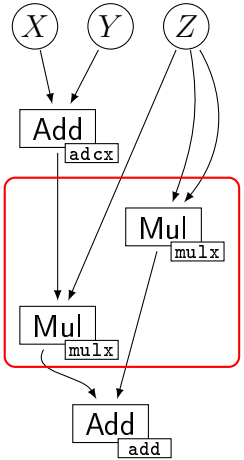


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mulx r8, r9, rax

mulx r10, r11, [Z]

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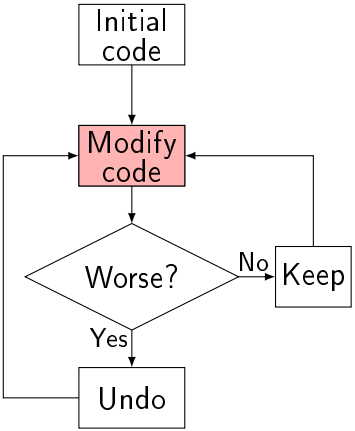
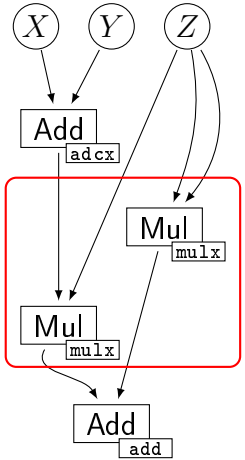
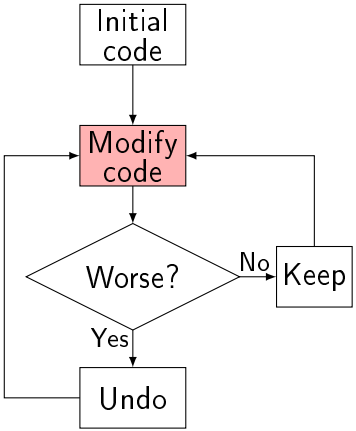
# Example Function: $(X + Y) \cdot Z + Z^2$

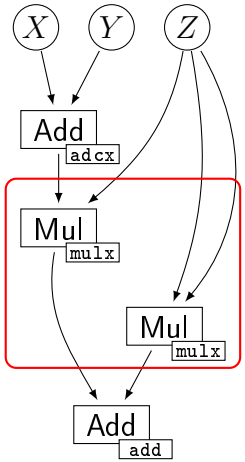



```
mov rax, [X]
clc
adcx rax, [Y]

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


mulx r10, r11, [Z]

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

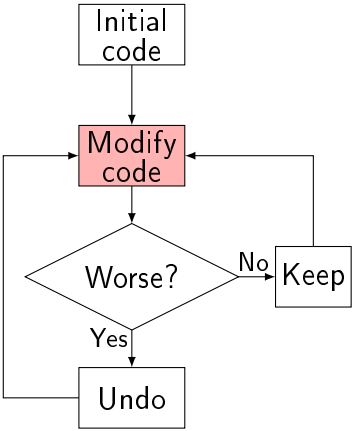
# Example Function: $(X + Y) \cdot Z + Z^2$ [reorder]

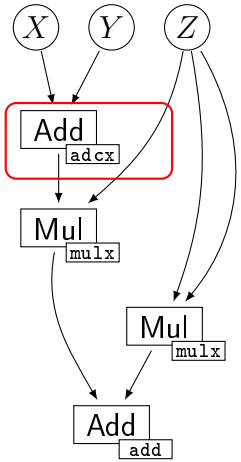



```
mov rax, [X]
clc
adcx rax, [Y]

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


mulx r8, r9, rax


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

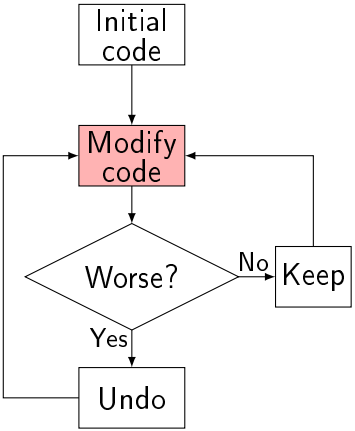
# Example Function: $(X + Y) \cdot Z + Z^2$ [template]

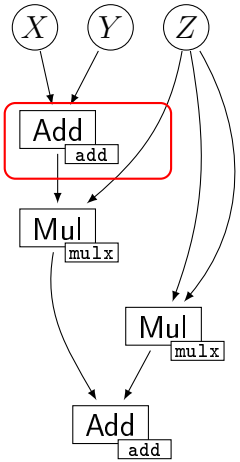



```
mov rax, [X]
clc
adcx rax, [Y]

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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clc
add rax, [Y]

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

mulx r8, r9, rax

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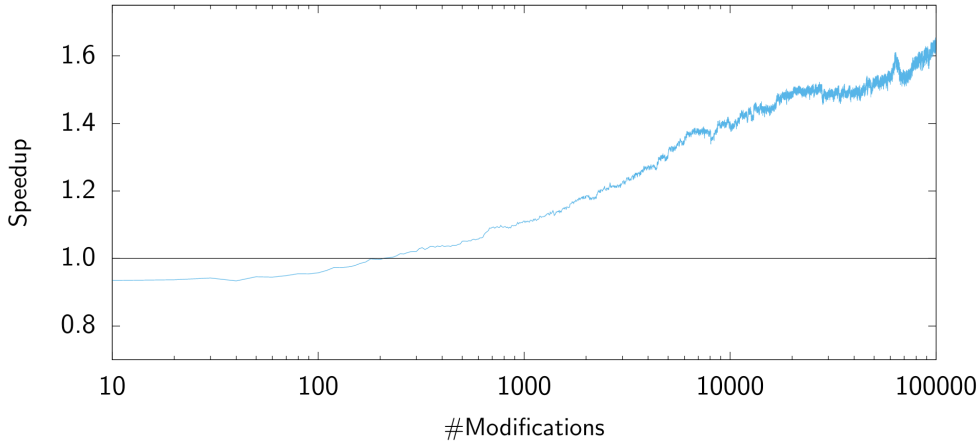
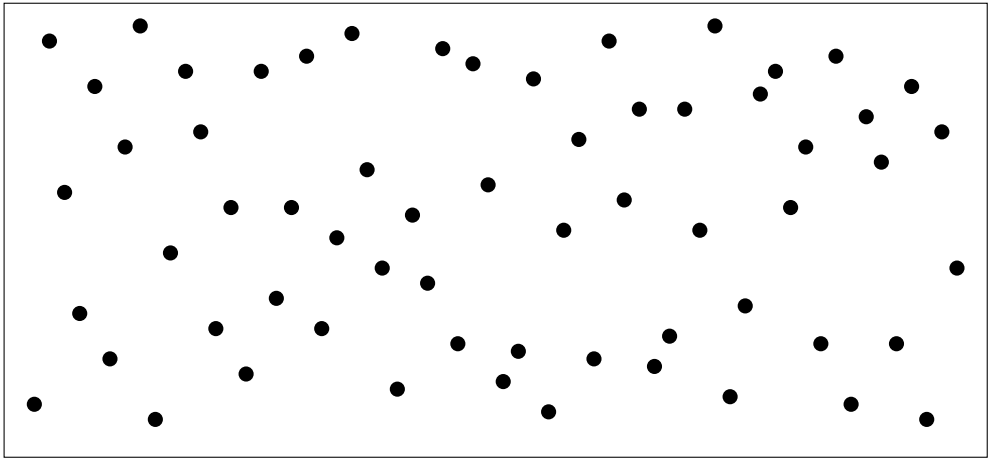
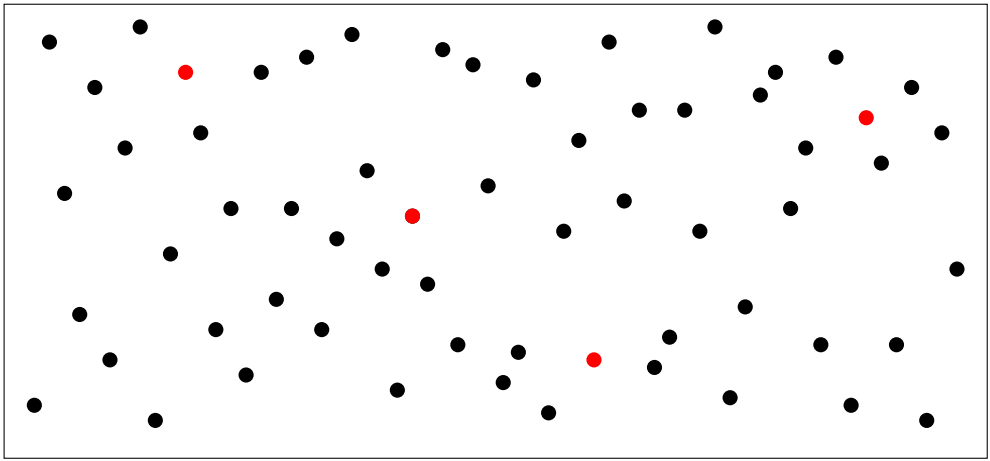

# Optimization Progress



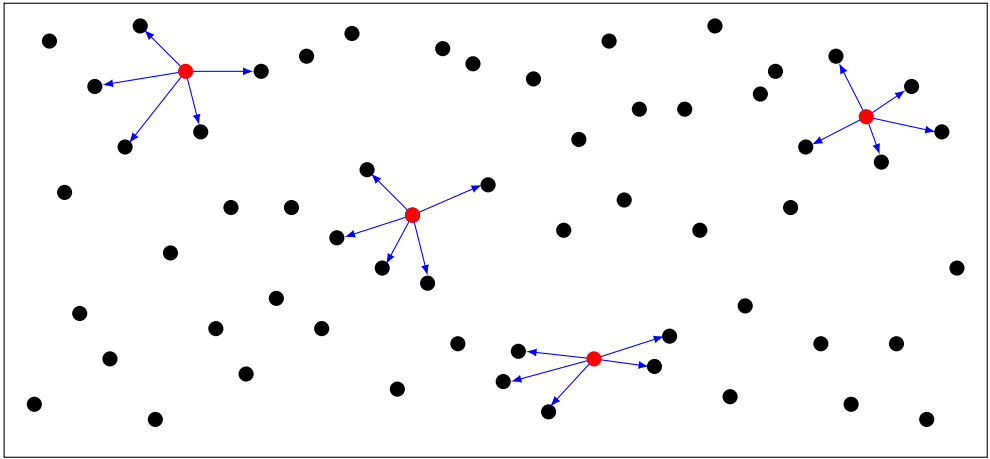
# Random Local Search with Bet-and-Run



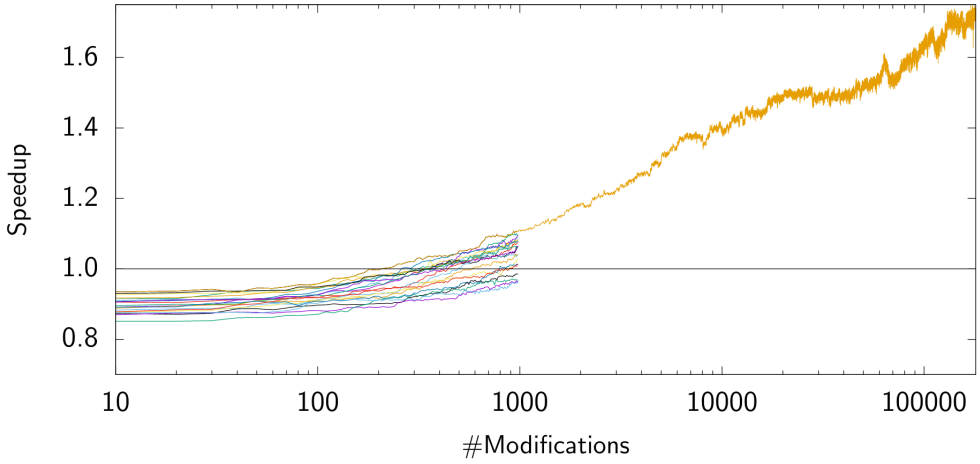
# Random Local Search with Bet-and-Run



# Random Local Search with Bet-and-Run



# Bet-and-Run in Action



# Fiat Cryptography

Fiat Cryptography
Erbsen et al.
IEEE S&P 2019

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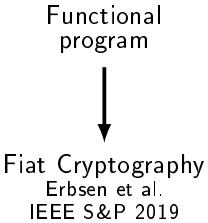

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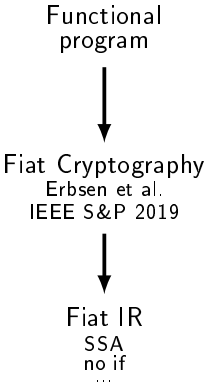

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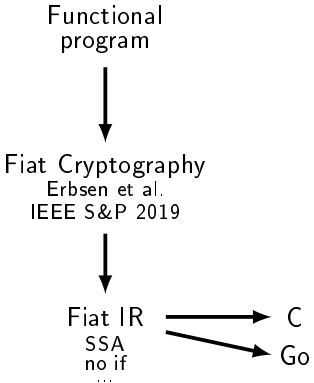

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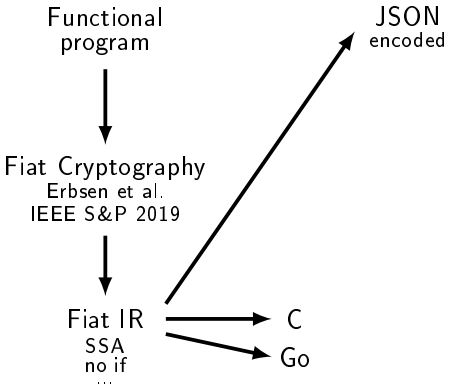

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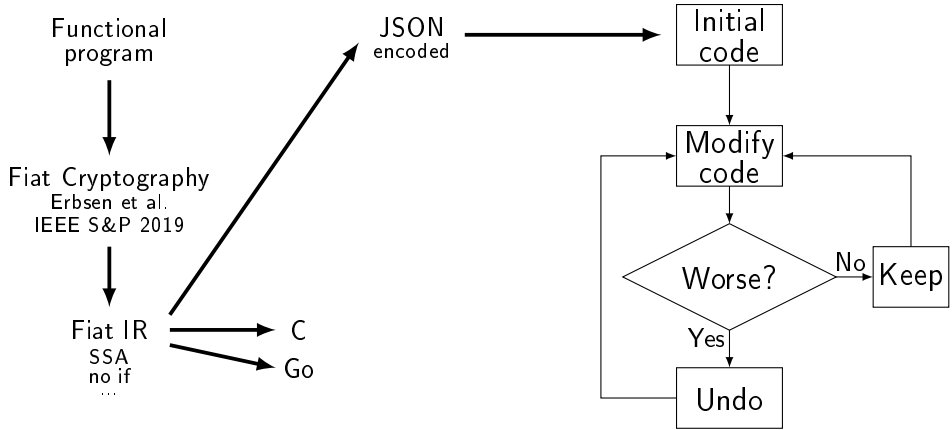

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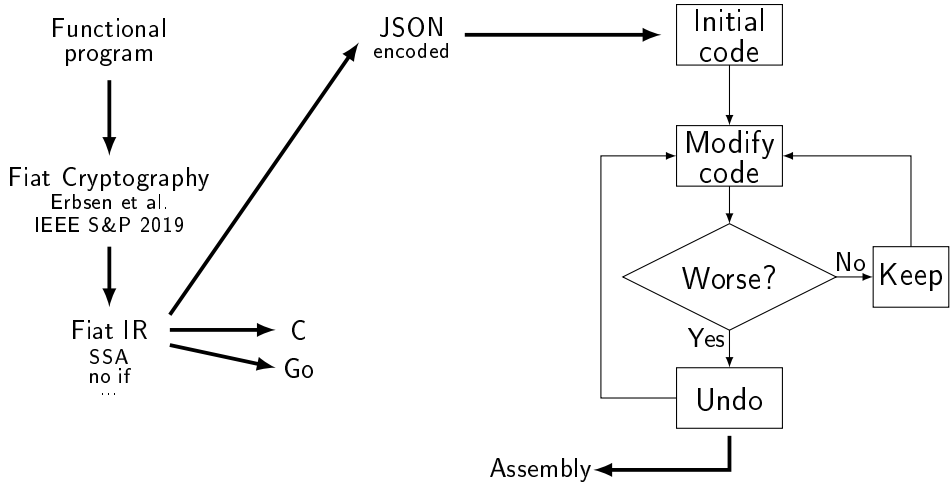

# Performance: Field Arithmetic

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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Geometric Mean (4x AMD, 6x Intel)

| | Multiply | | Square | |
|---|---|---|---|---|
| Curve | Clang | GCC | Clang | GCC |
| Curve25519 | 1.19 | 1.14 | 1.14 | 1.18 |
| P-224 | | | | |
| P-256 | | | | |
| P-384 | | | | |
| SIKEp434 | | | | |
| Curve448 | | | | |
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| Poly1305 | | | | |
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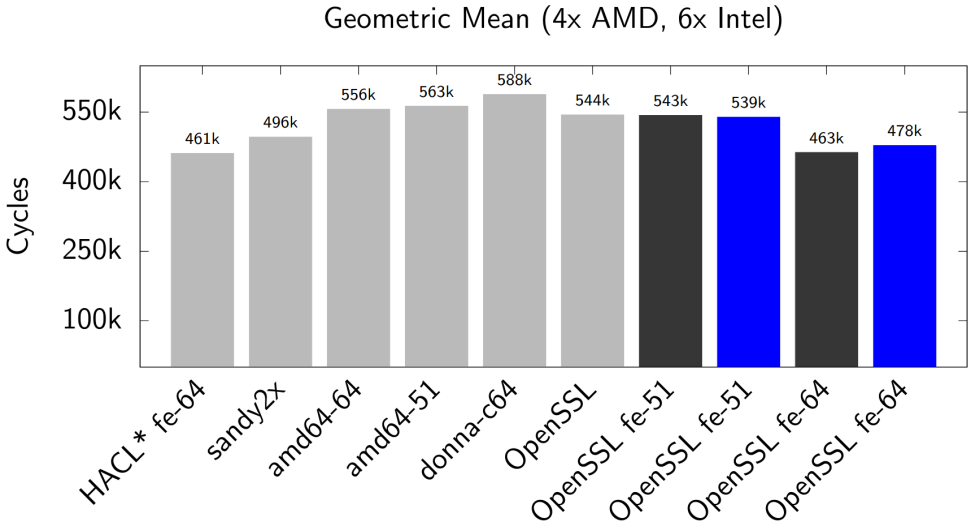
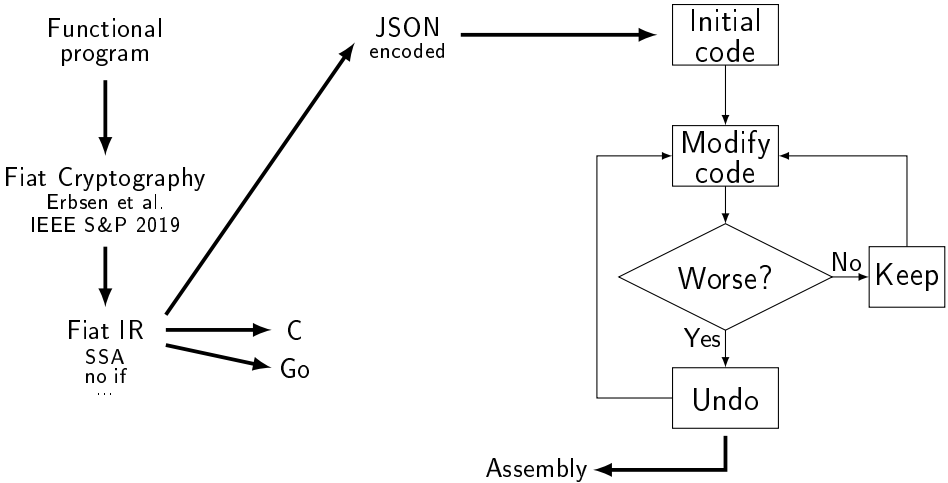
|---|---|---|---|---|
| Curve | Clang | GCC | Clang | GCC |
| Curve25519 | 1.19 | 1.14 | 1.14 | 1.18 |
| P-224 | 1.31 | 1.87 | 1.24 | 1.84 |
| P-256 | 1.27 | 1.79 | 1.30 | 1.85 |
| P-384 | 1.12 | 1.66 | 1.08 | 1.60 |
| SIKEp434 | 1.30 | 1.70 | 1.29 | 1.83 |
| Curve448 | 1.02 | 0.95 | 1.00 | 0.99 |
| 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



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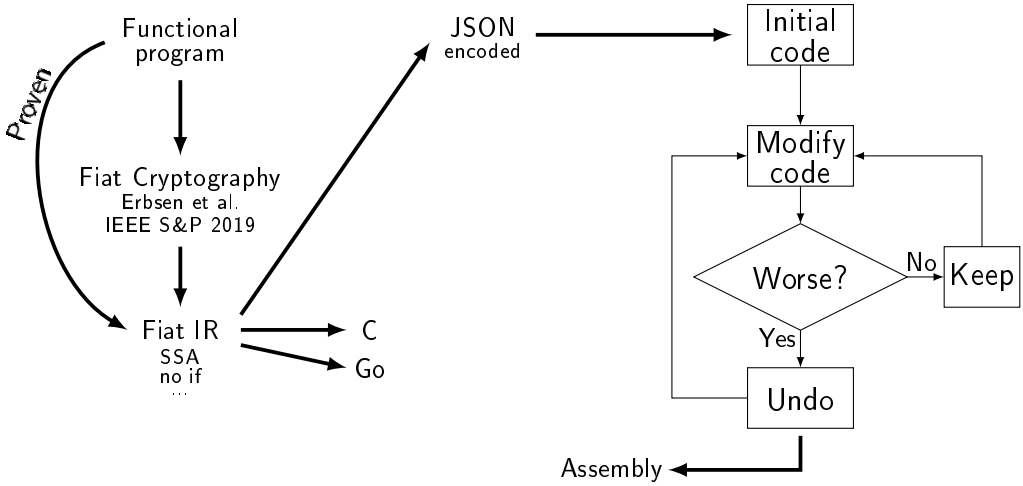

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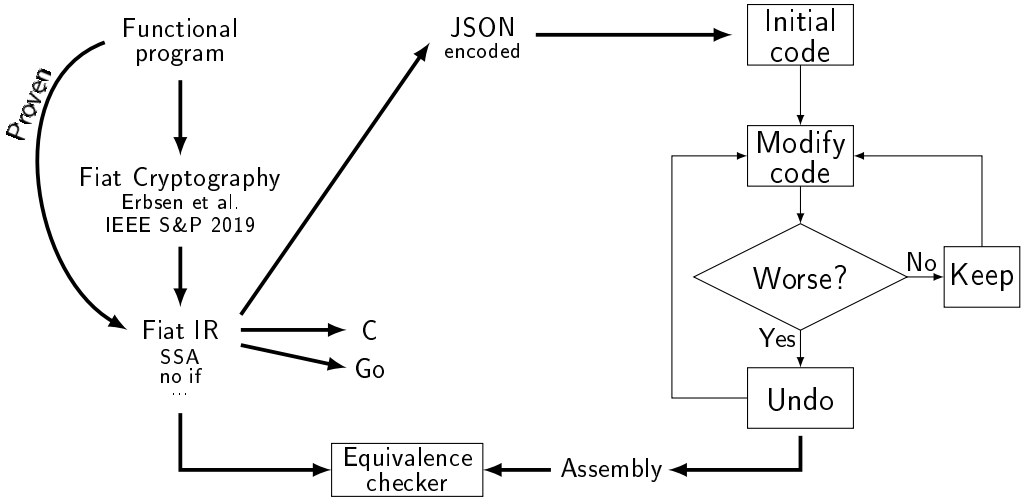
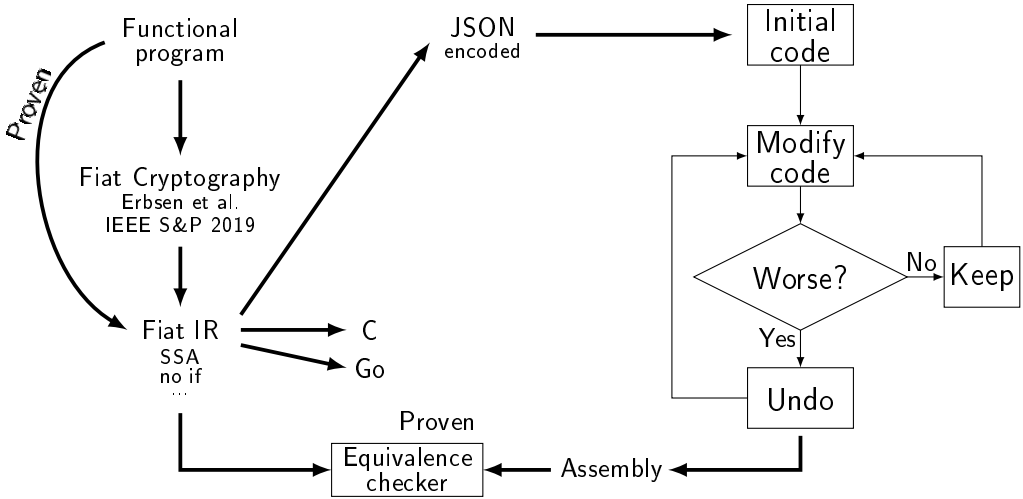


# Correctness



# Achievements

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GitHub Project

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GitHub Project

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- Integrated in Google's products including Chromium-base browsers