# Constant-Time Coding Support in LLVM: *Protecting Cryptographic Code at the Compiler Level*

LLVM 2025, 27th October, Julius Alexandre

# The Compiler Optimization Problem

**Modern compilers excel at making code run faster:**

- Eliminate redundant operations
- Vectorize loops for parallel execution
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**Break Cryptographic code...**

# Timing Attacks: The Silent Threat

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- CVE-2022-4304 (OpenSSL RSA - billions affected)
- CVE-2021-38153 (Apache Kafka authentication - Fortune 100 companies)
- CVE-2023-5388 (NSS RSA ~150M Firefox users)
- And more...

# Real-World Impact

**ETH Zürich Study: "Breaking Bad" (2024)**

- 8 production cryptographic libraries analyzed
- Tested on different compilers version for LLVM and GCC
- 44,604 experiments found compiler-induced vulnerabilities
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**Prior work:**

- Simon and Chisnall `__builtin_ct_choose` (2018)
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**Cryptographers current solution:**

- Using inline assembly
- Bitmask hack to bypass optimization
- Disable optimization

# Our Solution: __builtin_ct_select

**A new compiler intrinsic family:**

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**Key Properties:**

✓ Guarantees constant-time execution
✓ Preserved through all optimization levels
✓ Acts as optimization barrier
✓ Semantic meaning: "this must remain constant-time"
✓ All happening in the Post-RA

# Circumvent Branch-base Timing Attacks

## Carefully crafted constant-time code:

```
const bool cond = i == secret_idx;
result |= __builtin_ct_select(cond, table[i], 0);
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## Carefully crafted constant-time code:

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## x86 Assembly:

```asm
cmp    rdi, rcx            ; i == secret_idx
sete   dl                  ; Set dl = 1
test   dl, dl              ; Test the condition
mov    edx, 0              ; Prepare edx = 0
cmovne rdx, [rsi + 8*rcx]  ; CONDITIONAL MOVE
or     rax, rdx            ; result |= rdx
```

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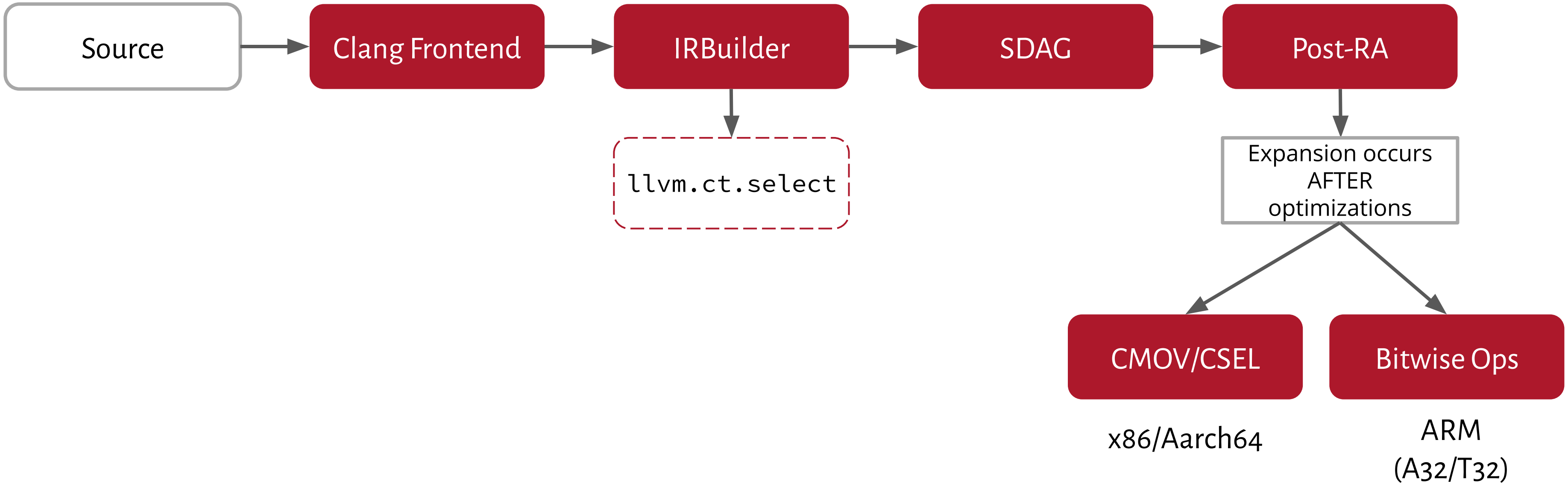
## ARM32 Assembly:

```
sub   r4, r0, r2        ; Arithmetic comparison
rsbs  r5, r4, #0
adc   r10, r4, r5
rsb   r4, r10, #0       ; Create explicit mask
and   r5, r6, r4        ; Explicit masking
orr   r3, r5, r3        ; Unconditional OR
```

# How It Works: Architecture Support

## NATIVE SUPPORT (x86, Aarch64 & Arm32)



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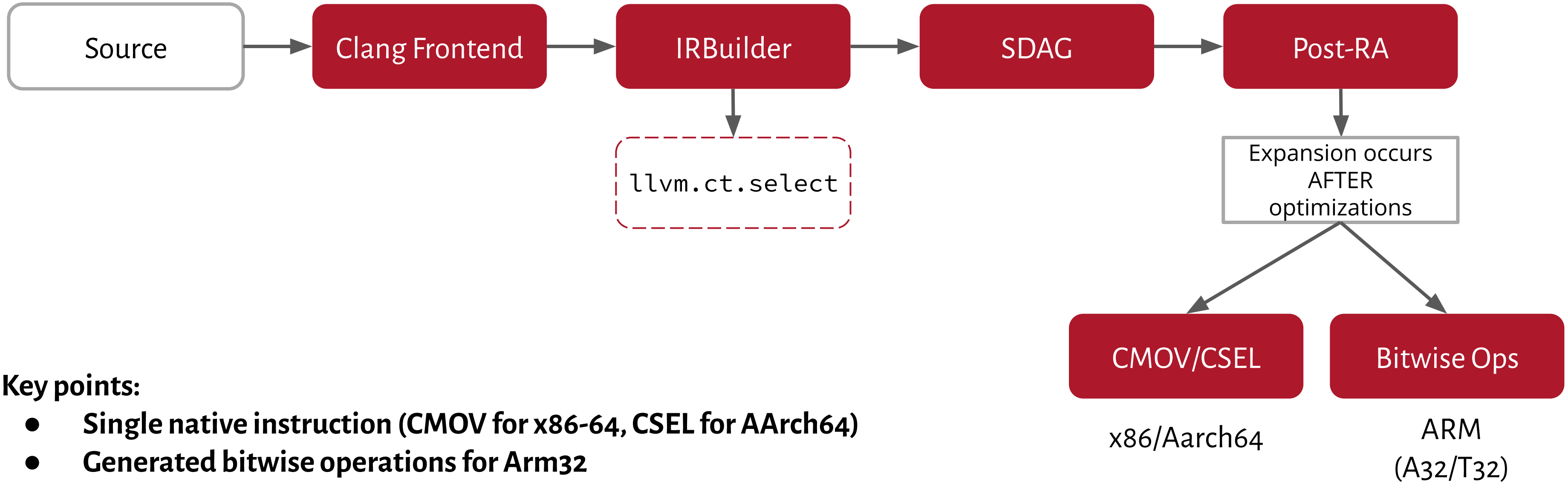


**Key points:**

- **Single native instruction (CMOV for x86-64, CSEL for AArch64)**
- **Generated bitwise operations for Arm32**
- **Constant-time enforced at Post-RA Expansion (AFTER all optimizations)**

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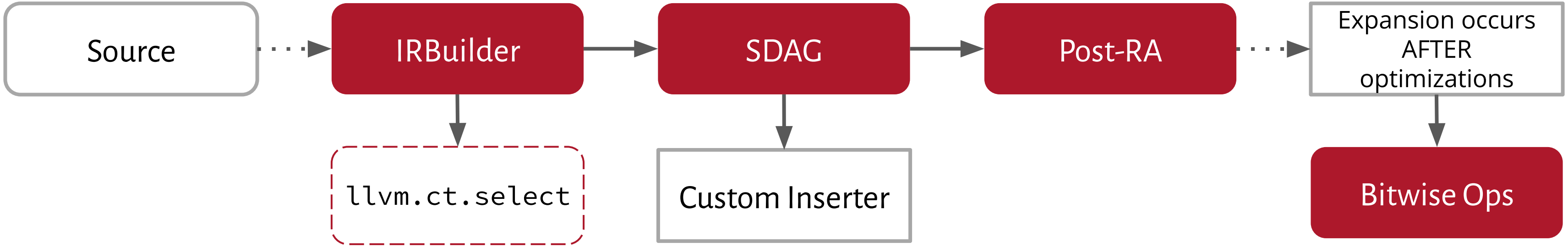
## NATIVE SUPPORT (i386)

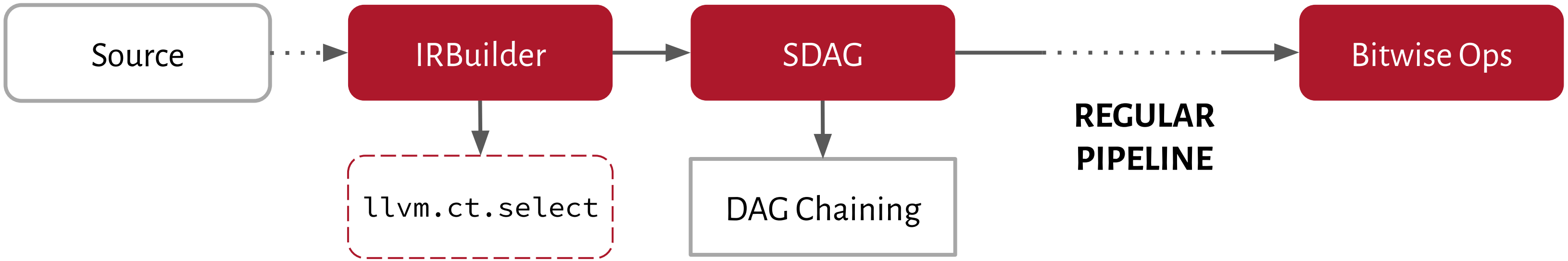



**Key points:**

- **Generates bitwise operations pattern (no CMOV available)**
- **UNIQUE two-phase approach (only architecture using both Custom Inserter + Post-RA)**

# How It Works: Architecture Support

## FALLBACK SUPPORT (RISC-V, Wasm, Mips, ...)




**Key points:**

- **Generates bitwise operations for said Architecture**
- **Constant-time enforced at SelectionDAG level**

# From RFC to Implementation

**Community Engagement:**
- RFC published on LLVM Discourse (August 2025)
- Strong support from cryptography maintainers
- Valuable feedback from LLVM developers

**Real-World benchmarking :**
- Tested BoringSSL, OpenSSL, etc
- Worked across multiple Architectures
- Better results compared

# Beyond C/C++: Language Support

**LLVM-based languages can leverage this work:**

**Rust:**

- Exploring intrinsics integration
- Safe wrappers in standard library

**Swift:**

- Apple can look into integrating our implementation

**WebAssembly:**

- Critical for browser-based cryptography

**Challenges:**

- GCC and Cranelift backend compatibility

# What's Next?

**Future Intrinsics:**

- `__builtin_ct<op>` for arithmetic operations
- `__builtin_ct_expr` for entire expressions
- Memory operations and string comparisons

**Goal: Make secure crypto practical in high-level languages**

# Key Takeaways

1. Compiler optimizations break constant-time guarantees
2. __builtin_ct_select provides compiler-level protection
3. Cross-architecture support
4. Community-driven approach with strong adoption
5. A crucial step toward practical secure cryptography