Compiling C Programs into a Strongly Typed Assembly Language

Takahiro Kosakai
Toshiyuki Maeda
Akinori Yonezawa
(Univ. of Tokyo)

Brief Overview

- We propose a method to guarantee the memory safety of C programs: **Compile C programs into a typed assembly language**
- Our contribution:
  1. Designed a typed assembly language **$CTAL_0$**
  2. Implemented an experimental compiler from C to $CTAL_0$

Outline

- Background
- Our Language: $CTAL_0$
- Implementation of Compiler
- Related Work
- Conclusion & Future Work

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Background (1/2)

- C is a classic programming language developed 35 years ago
- Even today, C is popular and a lot of security-critical software is written in C
  - Almost all of operating systems
  - Web servers
  - etc...

Background (2/2)

- However, C programs often have **memory-related** bugs that can easily lead to security vulnerabilities
  - Buffer overflow, dangling pointer, double free, ...
- About 40% of recent Linux kernel vulnerabilities are caused by memory-related bugs [1]

[1] SecurityFocus vulnerability database, January - June 2007.

Why so many memory bugs?

- Because C is **not** a **memory safe** language
  - E.g., No protection against out-of-bounds array access
    - **`array[i++] = 123;`**
    - May cause buffer overflow
- **Ensuring memory safety is a crucial step for ensuring security of software**

Existing Work

- There are several schemes to certify memory safety of C programs
- Two of such schemes are CCured [1] and Fail-Safe C [2]
  - Make C programs memory safe by program transformations
    - Inserting runtime bounds-checks, etc.

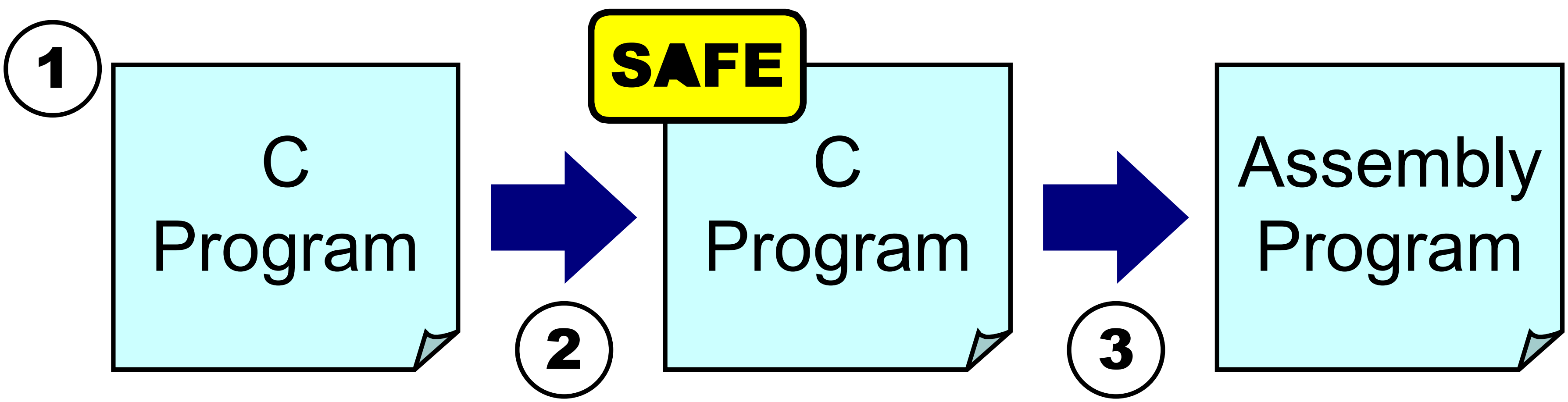
[1] G.C.Necula et al., *CCured: Type-safe retrofitting of legacy software*, TOPLAS '05.
[2] Y.Oiwa et al., *Fail-safe ANSI-C compiler: An approach to making C programs secure*, ISSS '02.

Problem with Existing Schemes

- They are source-to-source translators

Procedure for ensuring memory safety

1. Get source code of software
2. Apply the schemes to get certified source code
3. Compile it with conventional compiler (e.g., GCC)



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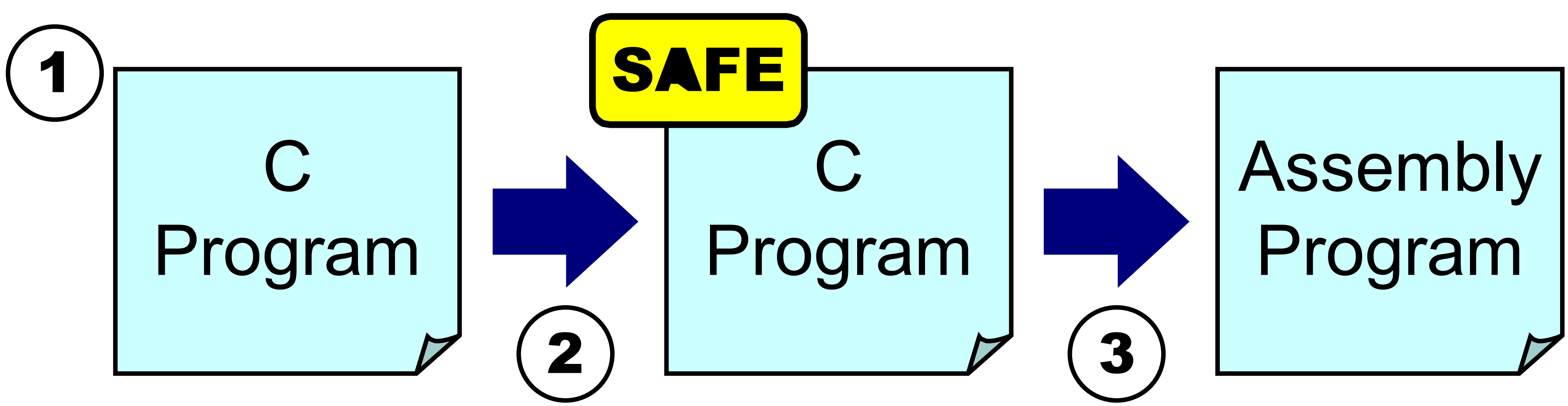

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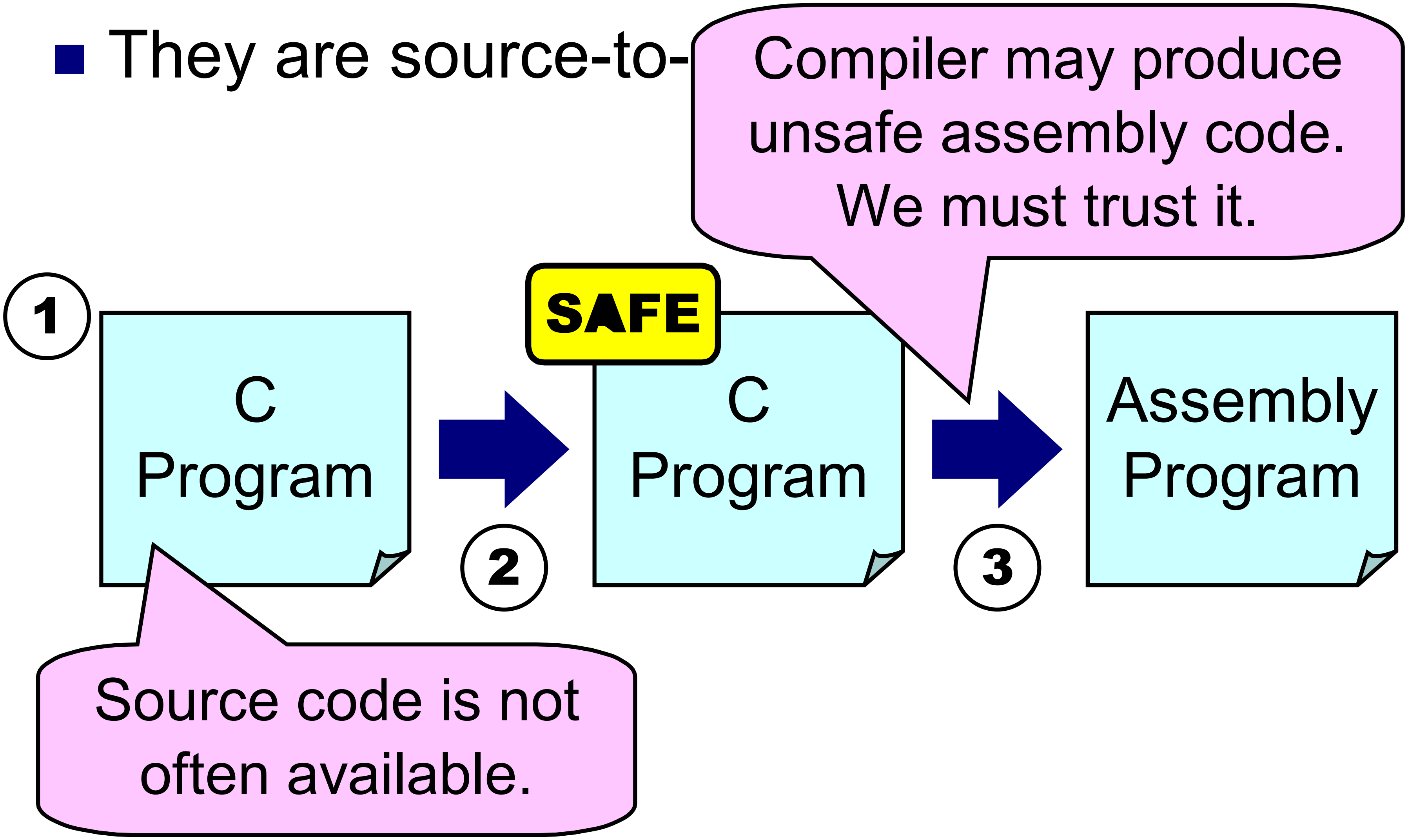
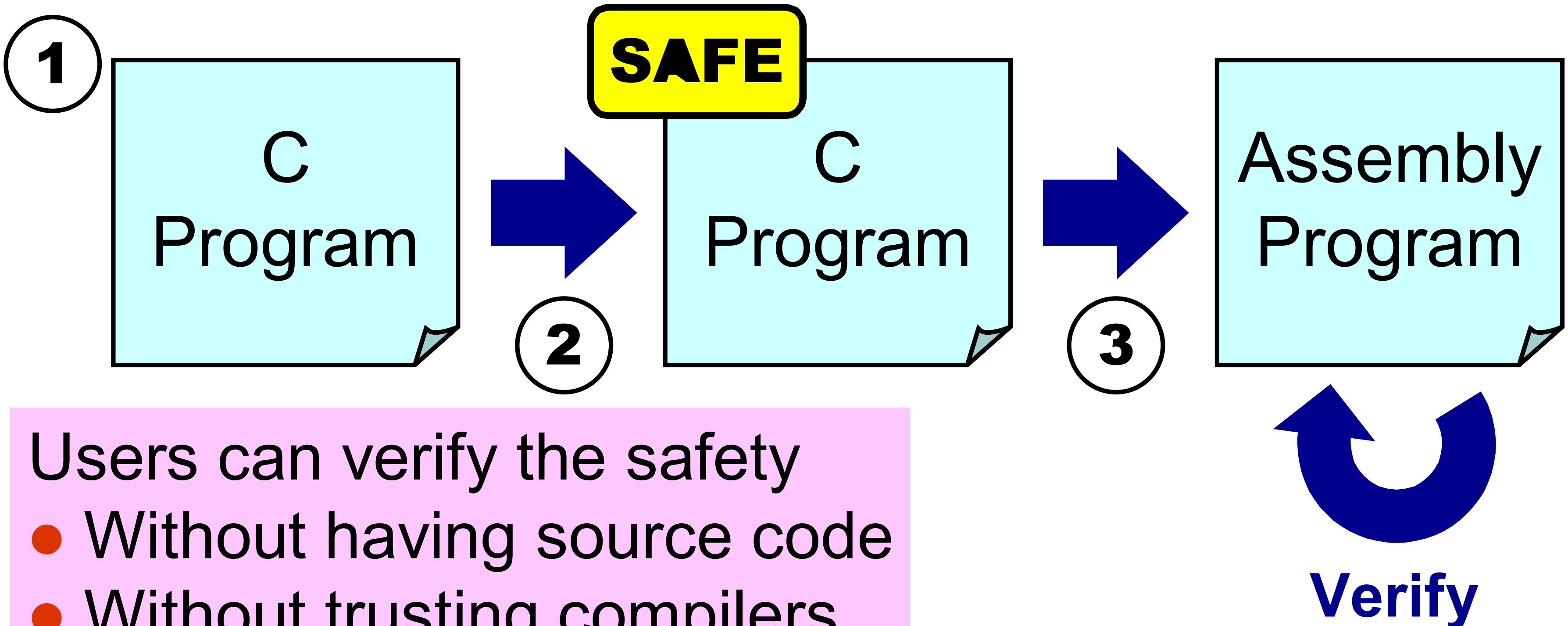


Our Approach

- Lower down the certification phase to **assembly-code level**



Users can verify the safety
- Without having source code
- Without trusting compilers

How to certify assembly code?

- We selected Typed Assembly Language (TAL) [1] as our starting point
- TAL is an assembly language equipped with a strong static type system
  - Well-typed assembly programs are memory safe
  - **Certification of memory safety can be done by simple type-checking**

[1] G.Morrisett et al., *From system F to typed assembly language*, POPL '98.

How to certify assembly code?

- TAL is not suitable for compiling from C
  - Its target is type-safe languages like ML
  - Operations that are not type-safe are not considered

- We propose an extension of TAL, called **$CTAL_0$**, which is aimed at C
  - It can handle lower-level issues such as non-type-safe casts and NULL pointers

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A flavor of $CTAL_0$

- Simple program named "**`inc`**" that loops infinitely, incrementing the value of register **`r1`**

{ **`inc`** $\rightarrow \forall(x)$. code[**`r1`**: Int(x)] }

```
inc:
   add r1, 1
   apply inc, (x → x + 1)
   jmp inc
```

Type annotation & Pseudo-instruction

Ordinary assembly code

A flavor of $CTAL_0$

Annotation of ***heap type***
Meaning: "At address **`inc`**, there is a value of type $\forall(x)$. code[**`r1`**: Int(x)]"

{ **`inc`** $\rightarrow \forall(x)$. code[**`r1`**: Int(x)] }

`inc:`

code[**`r1`**: Int(x)] denotes instruction sequences that are executable if **`r1`** has type Int(x)

Int(x) denotes integers whose value is exactly equal to x

Type-Checking in $CTAL_0$ (1/5)

- Type-checking proceeds by manipulating:
  - Γ : Type of each register
  - Ψ : Type of each value in the heap
  - ϕ : Valid logical formula over variables

{ **inc** $\rightarrow \forall(x)$. code[**r1**: Int(x)] }

```
inc:
  add r1, 1
  apply inc, (x → x + 1)
  jmp inc
```

Type-Checking in $CTAL_0$ (2/5)

- First, Γ, Ψ, ϕ are initialized according to the heap type annotation

Γ = [**r1**: Int(x)]
Ψ = { **inc** $\rightarrow \forall(x)$. code[**r1**: Int(x)] }

ϕ = True

{ **inc** $\rightarrow \forall(x)$. code[**r1**: Int(x)] }

```
inc:
   add r1, 1
   apply inc, (x → x + 1)
   jmp inc
```

Type-Checking in $CTAL_0$ (3/5)

- When checking **add**, Γ(**r1**) is updated so that it reflects the effect of **add**

Γ = [**r1**: Int(x + 1)]
Ψ = { **inc** $\rightarrow$ $\forall$(x). code[**r1**: Int(x)] }

ϕ = True

{ **inc** $\rightarrow$ $\forall$(x). code[**r1**: Int(x)] }

```
inc:
  add r1, 1
  apply inc, (x → x + 1)
  jmp inc
```

Type-Checking in $CTAL_0$ (4/5)

- Next **`apply`** pseudo-instruction instantiates the polymorphic type of **`inc`** in Ψ

Γ = [**`r1`**: Int(x + 1)]
Ψ = { **`inc`** $\rightarrow$ code[**`r1`**: Int(x + 1)] }

ϕ = True

{ **`inc`** $\rightarrow$ $\forall(x)$. code[**`r1`**: Int(x)] }

```
inc:
  add r1, 1
  apply inc, (x → x + 1)
  jmp inc
```

Type-Checking in $CTAL_0$ (5/5)

- Type-checking **`jmp`** is to check the current state matches the type of jump destination

Γ = [**r1**: Int(x + 1)]

match ➔ OK

Ψ = { **inc** $\rightarrow$ code[**r1**: Int(x + 1)] }

ϕ = True

{ **inc** $\rightarrow$ $\forall(x)$. code[**r1**: Int(x)] }

```
inc:
  add r1, 1
  apply inc,
➔ jmp inc
```

($x \rightarrow x + 1$)

This program successfully passes the type-checking

Extensions to TAL

- Key extensions in $CTAL_0$ that make it suitable for compiling from C
  - Two characteristic types
    - **Untyped array types**: Array(i)
    - **Guarded types**: $\phi\ ?\ \tau_1 : \tau_2$
  - Support of **byte addressing**

Untyped Array Types (1/2)

- Motivation
  - How to deal with non-type-safe casts?

```
int arr[3];
((char *)arr)[2] = 'A';
```

  - **`arr`** is an array of **`int`**, but it is also used as an array of **`char`**
  - Thus **`arr`** cannot have type "Array(**`int`**)" in a strongly typed language

Untyped Array Types (2/2)

- Denotes "untyped" memory blocks
  - $CTAL_0$ type system imposes no restrictions on their contents
  - Original TAL arrays are typed (all elements must have uniform type)
- Can deal with non-type-safe casts

```
int arr[3];
((char *)arr)[2] = 'A';
```

  - **arr** can be an untyped array

Guarded Types (1/2)

- Motivation
  - How to deal with NULL pointers?

$$\{\,\mathbf{p} \rightarrow \mathbf{int}\,\}$$

  - This heap type means: "A value of type **int** exists at address **p**"
  - We want to allow **p** to be NULL

Guarded Types (2/2)

- Guarded type $\phi\ ?\ \tau_1 : \tau_2$ is ...
  - equal to type τ_1, if logical formula ϕ is true
  - equal to type τ_2, if logical formula ϕ is false
- Can represent "maybe-NULL" pointers

$$\{\, \mathtt{p} \rightarrow (\mathtt{p} \mathrel{!=} 0)\ ?\ \mathtt{int} : \langle\rangle \,\}$$

  - This heap type means: "If **`p`** is non-zero, then an **`int`** value is at address **`p`**" — i.e., **`p`** is either NULL or a pointer to **`int`**

Byte Addressing

- All bytes in memory blocks are accessible
  - Original TAL only considers word-size access
  - This extension itself is straight-forward, but slightly complicates formalization and proof of language safety

Formal Properties

- Well-typed $CTAL_0$ programs are ...
  - Memory safe
    - Will ***never*** perform wrong memory accesses
  - Control-flow safe
    - Will execute ***only*** valid instructions

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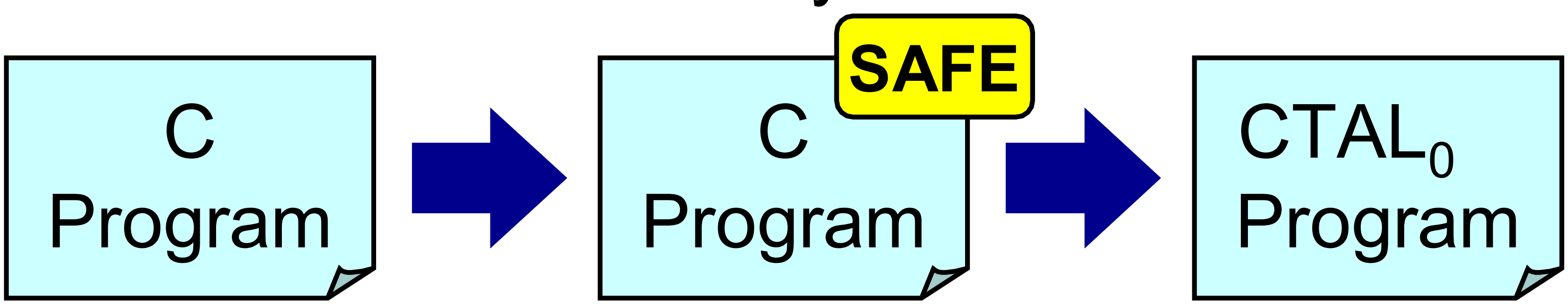
Compiling Strategy

- It is impossible to directly compile unsafe C programs into safe $CTAL_0$
- Our compiler takes 2 steps
  - First, establish safety by source-level program transformation
  - Then, compile it to $CTAL_0$, preserving the established safety



Program Transformation

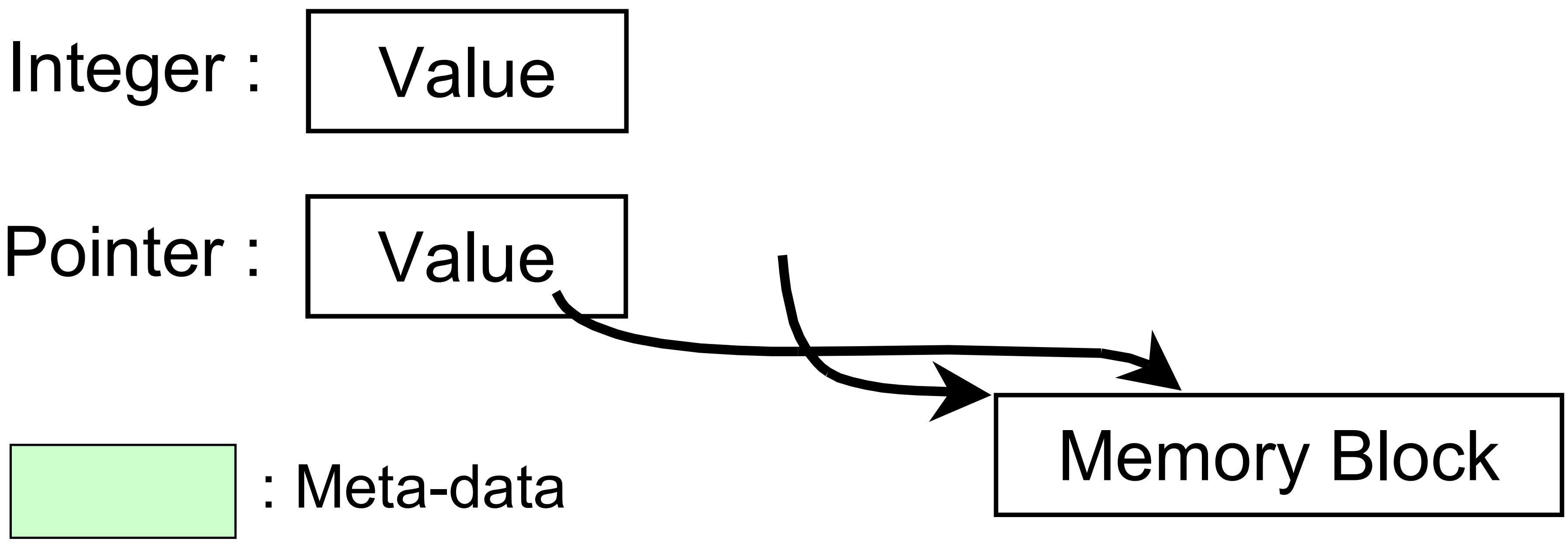
- Basically, insert bounds-checks before every memory dereference operation
  - Program will abort before doing wrong memory accesses
- To obtain correct bounds information for each pointer, we add some **meta-data**
  - Using several techniques of Fail-Safe C [1]

[1] Y.Oiwa et al., *Fail-safe ANSI-C compiler: An approach to making C programs secure*, ISSS '02

Transformation: Step 1 / 3

- Extend each integer and pointer to 2 words
  - **"Fat integer"**

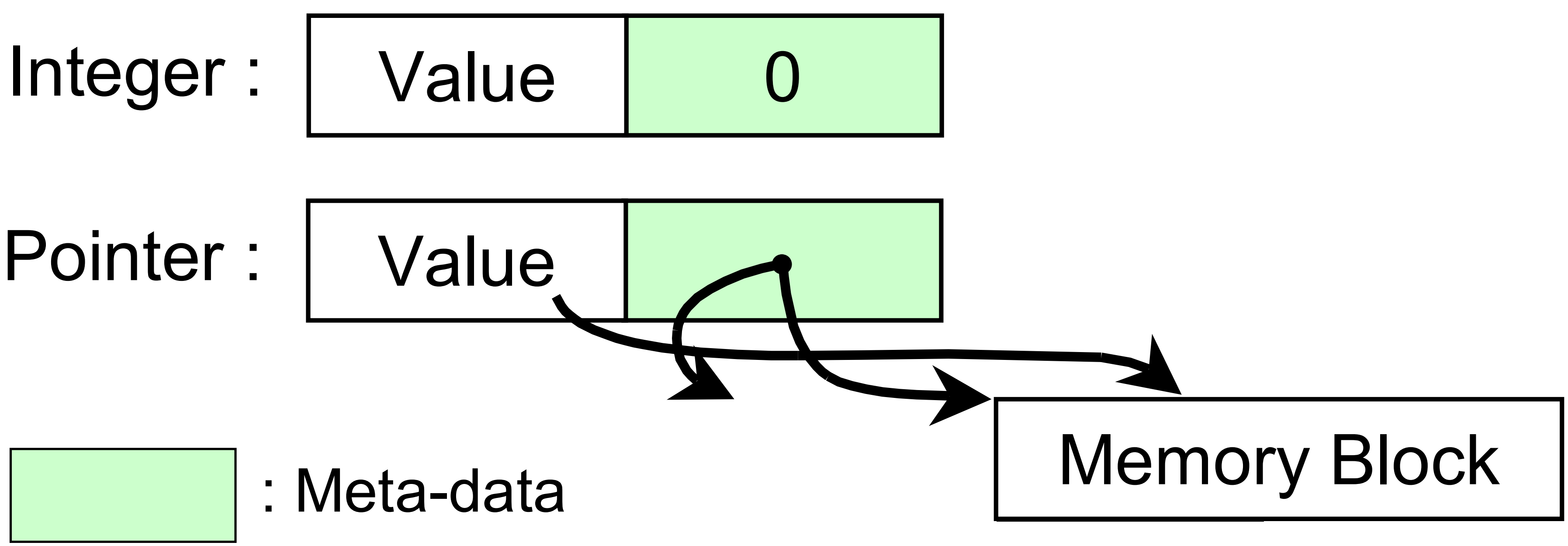
Casts between integers and pointers are freely possible



Transformation: Step 2 / 3

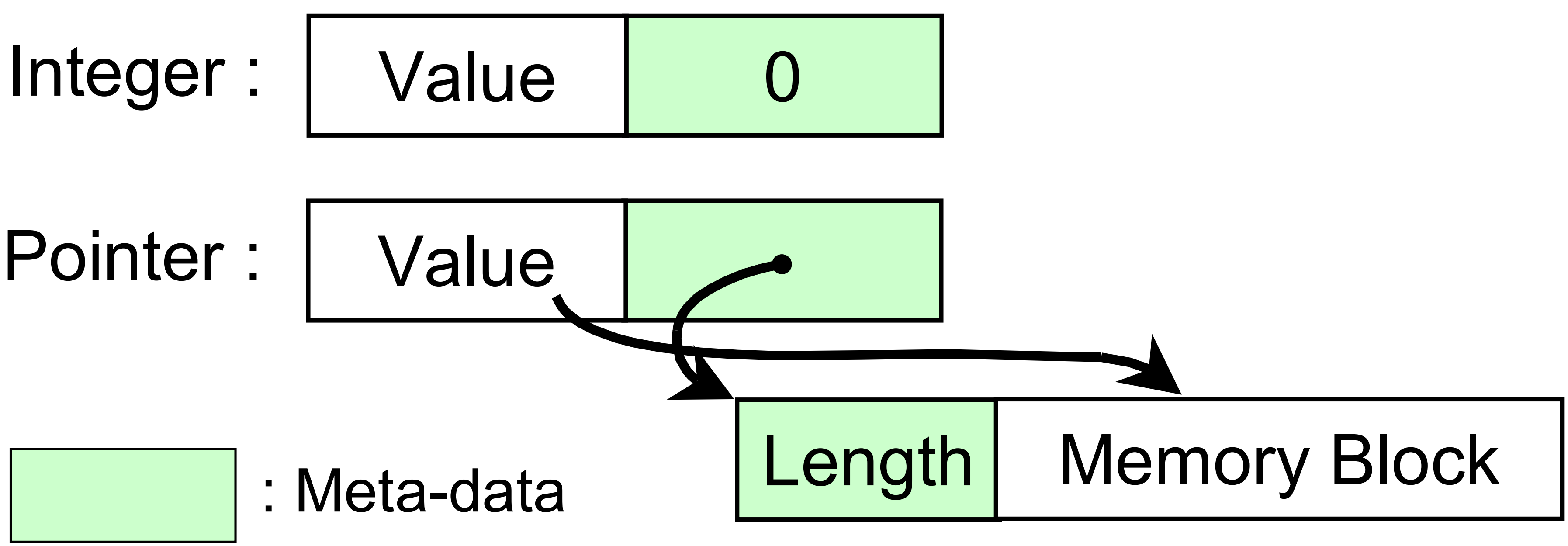
- Attach to every memory block its length

Bounds checks are now possible



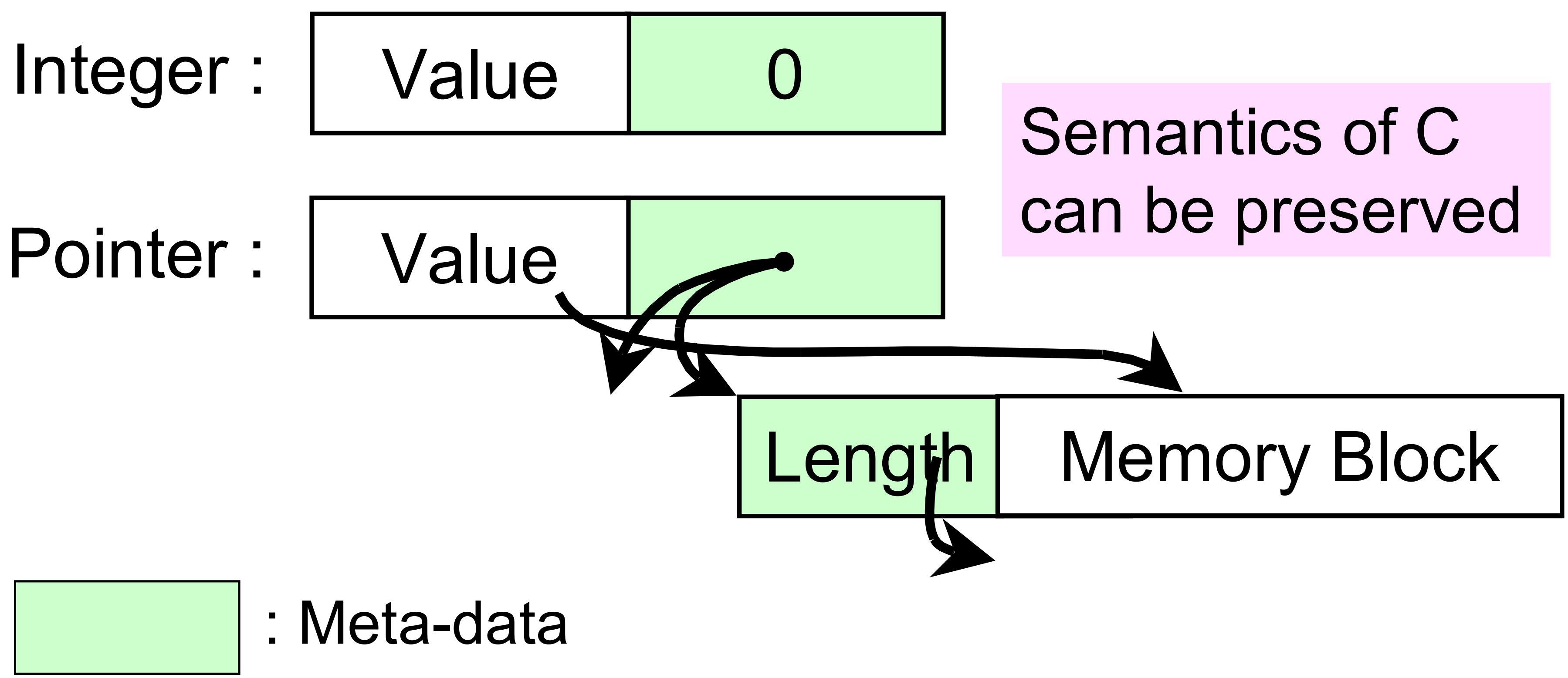
Transformation: Step 3 / 3

- Since integers are doubled in size, memory blocks should also be doubled



Transformation: Step 3 / 3

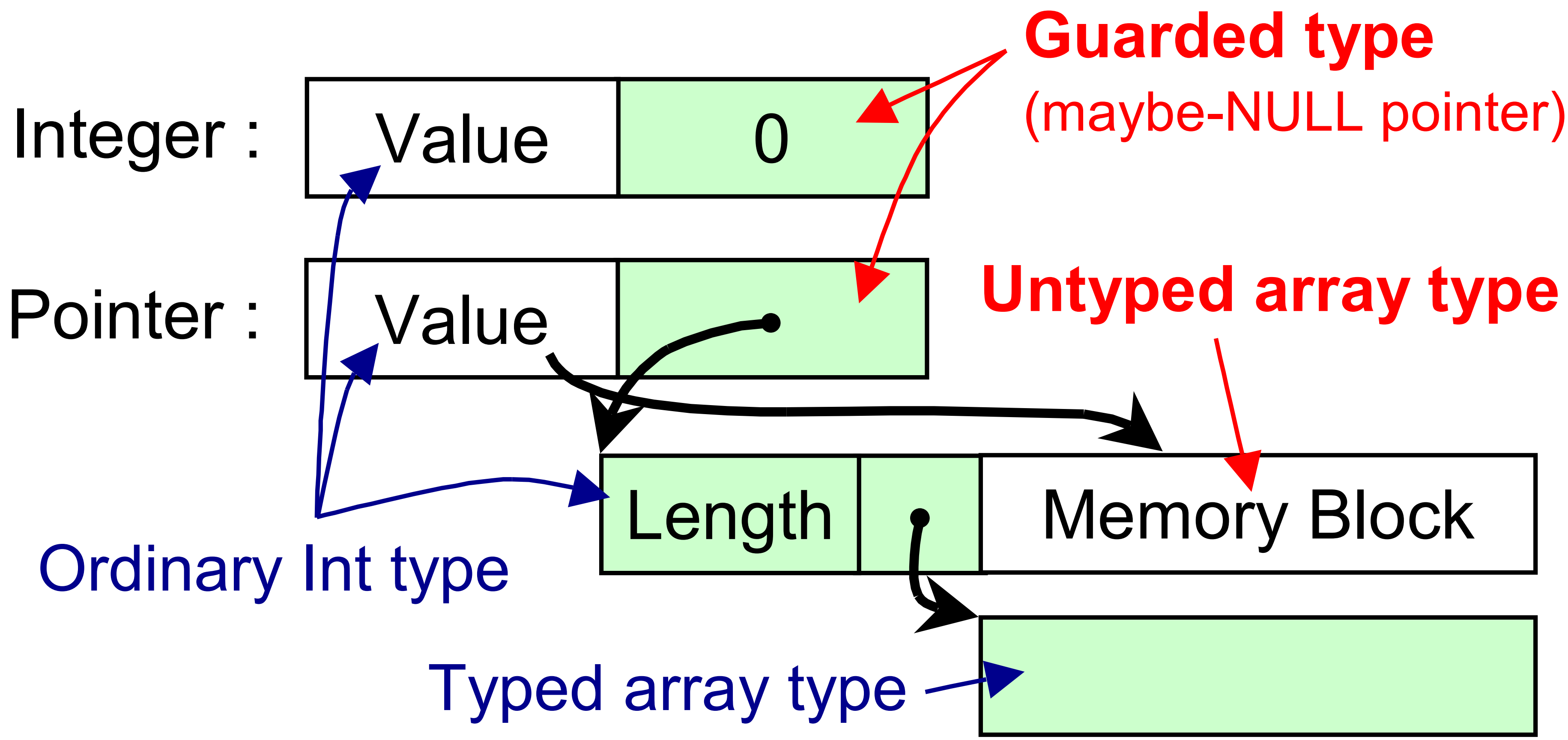
- Since integers are doubled in size, memory blocks should also be doubled



Semantics of C can be preserved

Typing

- This structure can be typed in $CTAL_0$



Supported Features

- Casts between integers and pointers
  - Using fat integers
- Arrays, structures, unions
  - By treating them as untyped arrays
- Function pointers
- Dynamic memory allocation (`malloc`)

Preliminary Experiment

- We have successfully compiled ...
  - Simple insertion sort program
  - glibc's quick sort function
    - Heavily uses function pointers
  - Huffman-code compressor
  - xvgif (GIF image decoding library)
    - Successfully detected and prevented a known buffer overflow bug
  - etc.

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Related Work

- CCured [1], Fail-Safe C [2]
  - Ensure memory safety of C programs
  - Good runtime performance
  - Source-to-source translators; there is no safety guarantee on assembly code

[1] G.C.Necula et al., *CCured: Type-safe retrofitting of legacy software*, TOPLAS '05.
[2] Y.Oiwa et al., *Fail-safe ANSI-C compiler: An approach to making C programs secure*, ISSS '02.

Related Work

- Typed Assembly Language [1]
  - Basis of our language $CTAL_0$
  - Mainly aimed at compiling from ML-like type-safe functional languages
- TALx86 [2]
  - TAL for Intel IA-32 architecture
  - Mainly aimed at compiling from Popcorn (an imperative, safe language)

[1] G.Morrisett et al., *From system F to typed assembly language*, POPL ’98.
[2] G.Morrisett et al., *TALx86: A realistic typed assembly language*, WCSSS ‘99

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Conclusion

- We have proposed a new typed assembly language $CTAL_0$, based on TAL
  - Guarantees memory safety at assembly-code level
- We have implemented an experimental compiler from C to $CTAL_0$
  - Supports free intermixing of integers and pointers, arrays, structures, unions, and function pointers

Future Work

- Improve compiler implementation
  - Optimization and static analysis to remove redundant dynamic checks
  - Binary compatibility with existing libraries
- Enrich $CTAL_0$'s type system
  - Support explicit memory deallocation
  - Support linking of object files

Fin.