Verified Compilation of C Programs with a Nominal Memory Model

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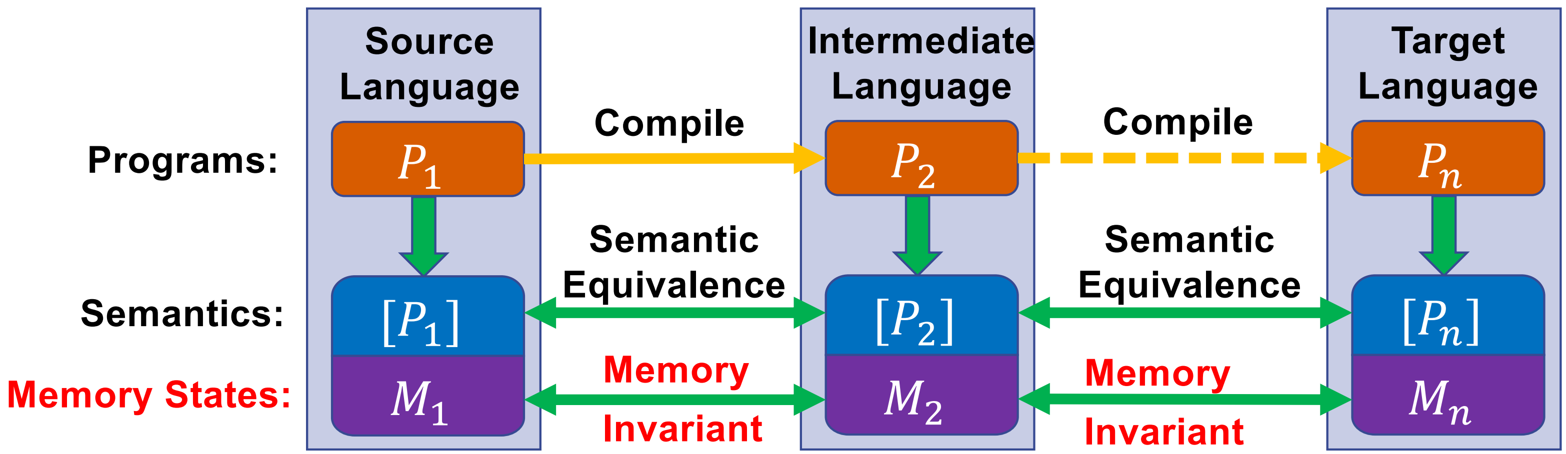
Background

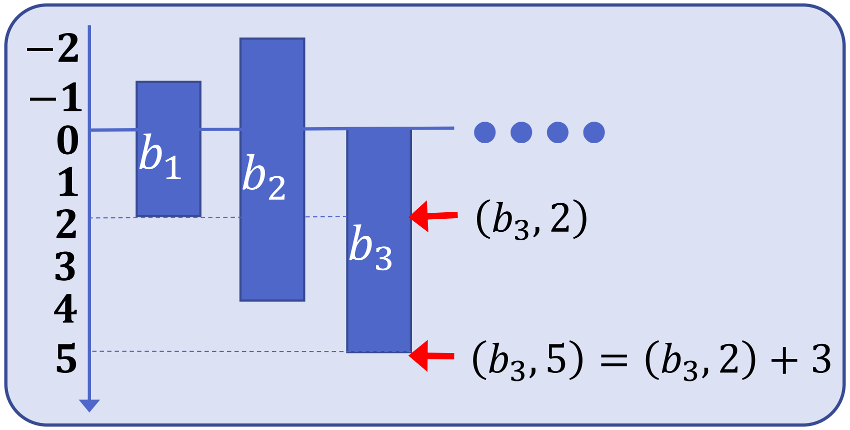
- **Memory Models in Verified Compilation**
  - Semantics for languages based on some memory model
  - Prove preservation of semantics with memory invariants



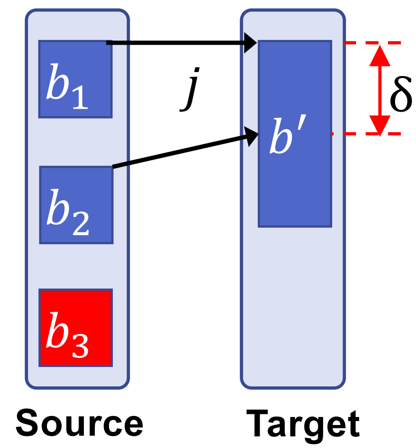
The Structure of Verified Compilers

The State-of-the Art

- **Block-Based Memory Model**
  - Memory model for CompCert
  - Pointers:
    - a pair (b, δ) of block id b and offset δ
  - Pointer Arithmetic:
    - $(b, \delta) + n = (b, \delta + n)$
  - Memory isolation by definition



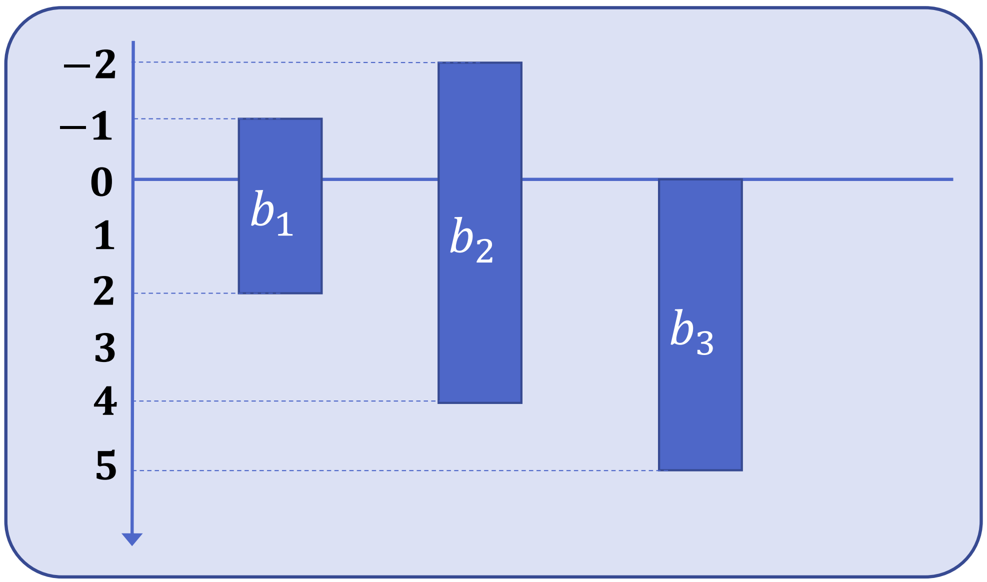
- **Injections as Memory Invariants**
  - An injection function j is a partial mapping for blocks
  - $j(b) = Some(b', \delta)$ if b is embedded into b' at offset δ
  - $j(b) = None$ if b is pulled out of the memory



- $j(b_1) = Some(b', 0)$
- $j(b_2) = Some(b', \delta)$
- $j(b_3) = None$

Restrictions

- **Concrete Numbering of Memory Blocks**
  a) Block identifiers are positive numbers: $1, 2, \ldots, n, \ldots$
  b) A special identifier called $nextblock$ for allocating fresh blocks
  c) Valid blocks are $\{1, 2, \ldots, nextblock - 1\}$

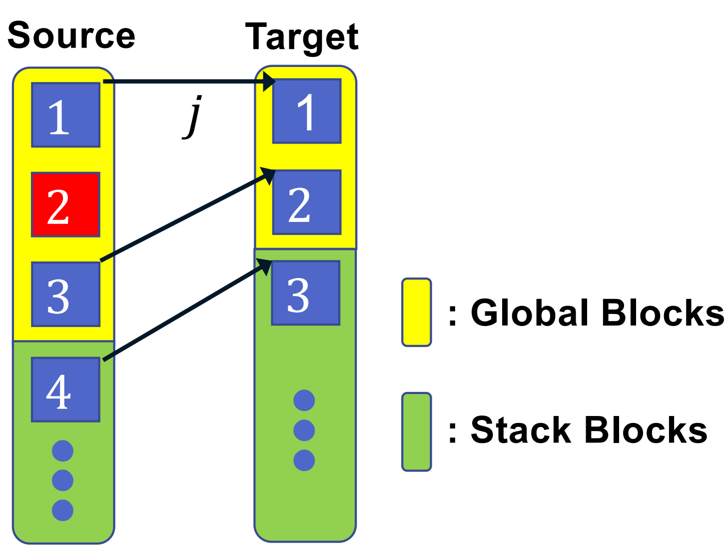


- $b_1 = 1$
- $b_2 = 2$
- $b_3 = 3$

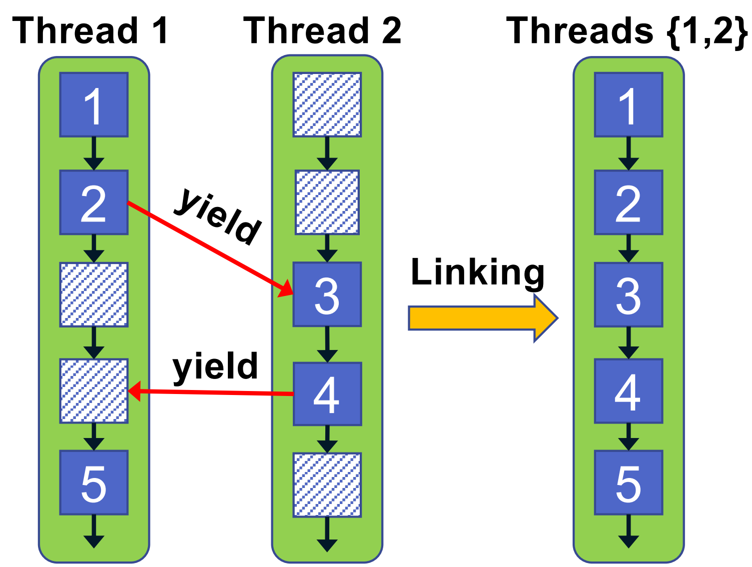
- $nextblock = 4$

Problems

1. No distinction between different memory regions
2. Contiguous numbering brings unnecessary dependency
3. Global constraint imposed by $nextblock$



Elimination of Unused Global Variables



Linking of Multi-Threaded Programs

Big Picture

Treatment of Named Resources in Formal Verification

1. Is there a more flexible representation of memory space?
2. What benefits it brings to compiler verification?

Our Contributions

- **Nominal Memory Model:** Generalization of Block-Based Memory Model
  - Flexible representation of blocks based on nominal techniques
  - Eliminates unnecessary dependency and global constraints
  - *Compatible with all existing mechanisms in BBMM*

- **Nominal CompCert:** A General Framework for Verified Compilation of C
  - Proofs are abstracted over the interface of nominal memory model
  - Supports complex memory structures through instantiation

- **Application of Nominal CompCert**
  - Verified compilation with structured memory
  - Verified contextual compilation to multi-stack machines

Memory Representation with Nominal Names

- **Background: Nominal Techniques for Managing Named Objects**
  - Names are represented as atoms in countably infinite sets
  - Renaming is described as permutations (bijection) on atoms
  - A set A of atoms supports an object x if

    $\forall\, \pi, \pi(x) = x$ (π denotes a permutation on atoms that is identity for A)

  - A name a (atom) is fresh to x if a is not in some support A
- **Key Ideas:**
  - Atoms to generalize block ids
  - Permutation is equivalent to (renaming-based) memory injection
  - Supports to generalize valid block ids
  - Freshness to generalize $nextblock$
- **Note:** We do not yet exploit the analogy between permutation and injection

Nominal Memory Model

An Abstraction of Block-Based Memory Model with a Nominal Interface

Interface of the Nominal Memory Model

```
(* Block ADT *)
Module Type BLOCK.
  Parameter block : Type.
  Parameter eq_block : ∀ x y : block, {x = y} + {x ≠ y}
End BLOCK.

(* Support ADT *)
Module Type SUP.
  Parameter sup : Type.
  Parameter sup_empty: sup.              (* Empty Support *)
  Parameter fresh_block: sup → block.    (* Fresh Block *)
  Parameter sup_incr : sup → sup.        (* Increase Support *)
  (* Check Validity of Blocks*)
  Parameter valid_block : block → sup → bool.
  ...
End SUP.
```

Block-Based Memory Model

```
(* Block ADT *)
Module Block <: BLOCK.
  Definition block := positive.
  Definition eq_block := peq.
End Block.

(* Support ADT *)
Module Sup <: SUP.
  Definition sup := list block.
  Definition sup_empty : sup = [].
  Definition fresh_block (s: sup) := (max s) +1.
  Definition sup_incr (s: sup) := (fresh_block s) :: s.
  (* Check Validity of Blocks*)
  Definition valid_block (b: sup) (s: sup) := b ∈ s.
  ...
End Sup.
```

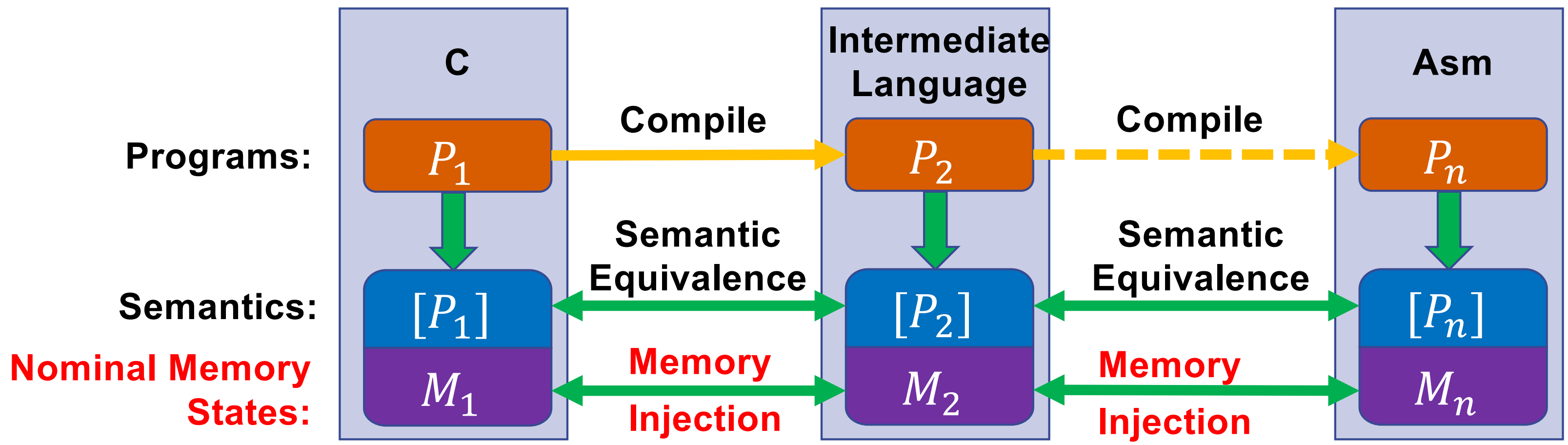
Benefits

Problems:		**Solutions:**
1. No Distinction of Memory Regions	⇒	1. Block Type for Classifying Memory
2. Contiguous Numbering of Blocks	⇒	2. Support Type for Separating Memory
3. Global Constraint from $nextblock$	⇒	3. $fresh\_block$ for Localized Allocation

All operations, properties and proofs remain (almost) unchanged!

Nominal CompCert

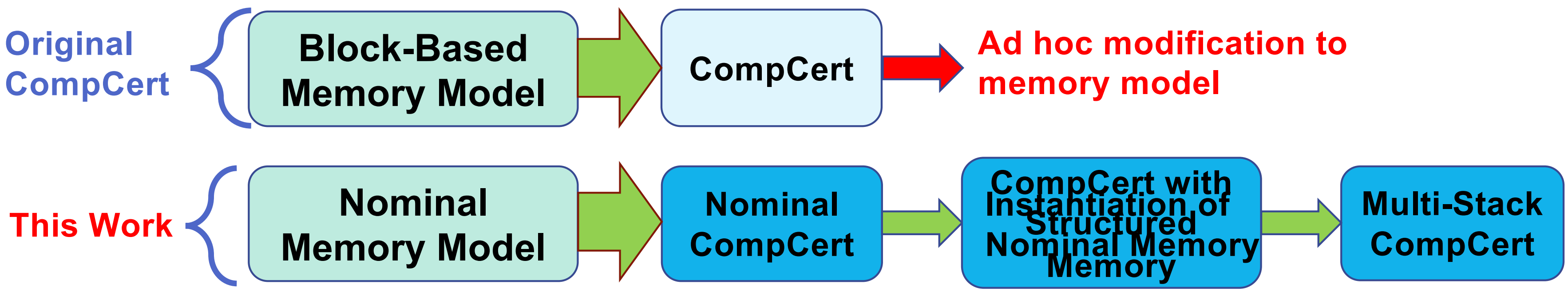
A Complete Extension of CompCert with the Nominal Memory Model



The Structure of Nominal CompCert

- **Abstraction:** Proofs hold under any instantiation of nominal interface

Enhanced Verified Compilation



1. Verified Compilation with Structured Memory
2. Verified Contextual Compilation to Multi-Stack Machines

Structured Memory Space

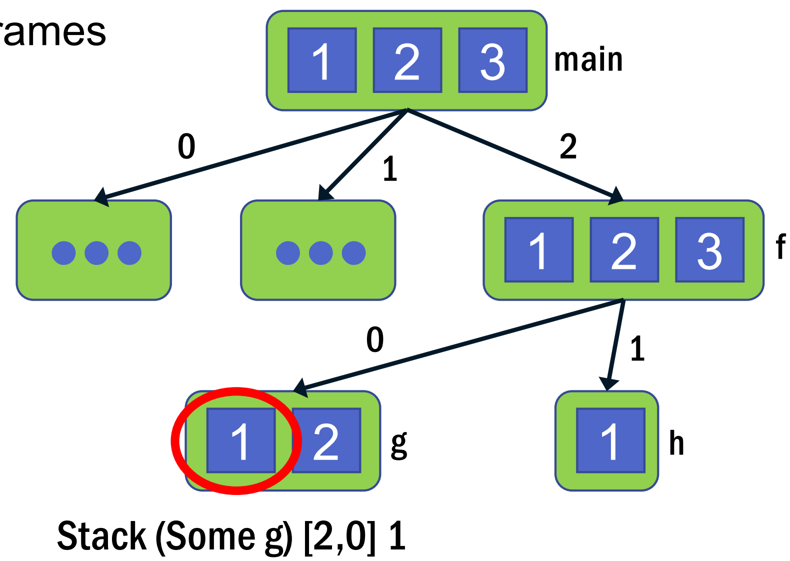
- **Key Idea:** Rich memory structures via instantiating blocks and supports
- **Memory Space = Global Space + Stack Space**

```
Record sup := {global           ; stack        }.
```

  - Global blocks are given static names
  - Stack space is organized into a tree of frames
  - Note: Heap is part of global memory

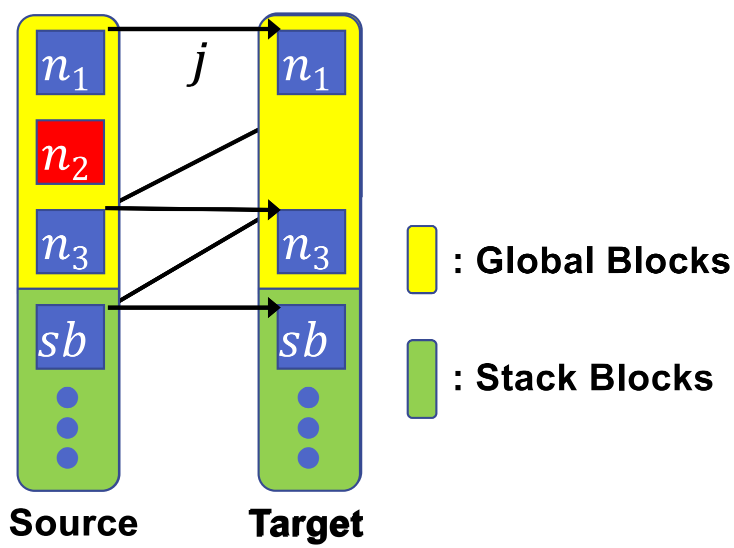
- **Block Type:**

```
Inductive block :=
| Global : ident → block.
| Stack  :  option ident → list nat → positive → block;
```



Structural Injection Functions

- Represent memory invariant by static injection functions
- **Example:** Elimination of Unused Global Variables



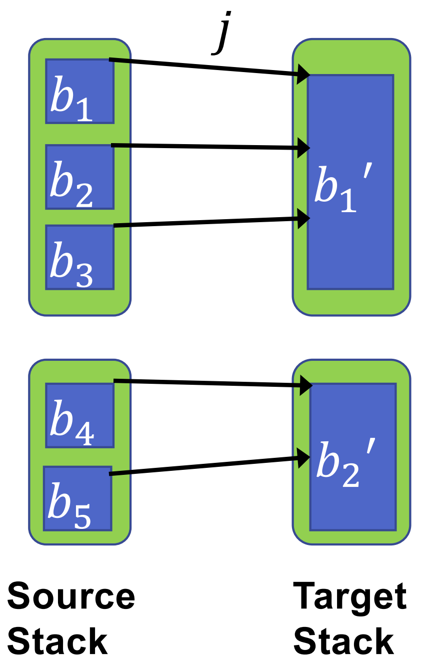

```
Variable ge: genv.  (* target environment *)

Definition check_block (s:sup) (b:block): bool :=
 match b with
 | Stack _ _ _ ⇒ valid_block b s
 | Global i ⇒ match (find_symbol ge i) with
                 | None ⇒ false | Some _ ⇒ true
               end
 end.

Definition struct_meminj (s:sup) (b:block) :=
 if check_block s b then Some (b, 0) else None.
```

Reasoning about Local Memory Transformations

- **Observation:** Many transformation focuses on local memory regions
- Structural injections capture local memory transformations
- **Example:** Merging of Stack-Allocated Variables



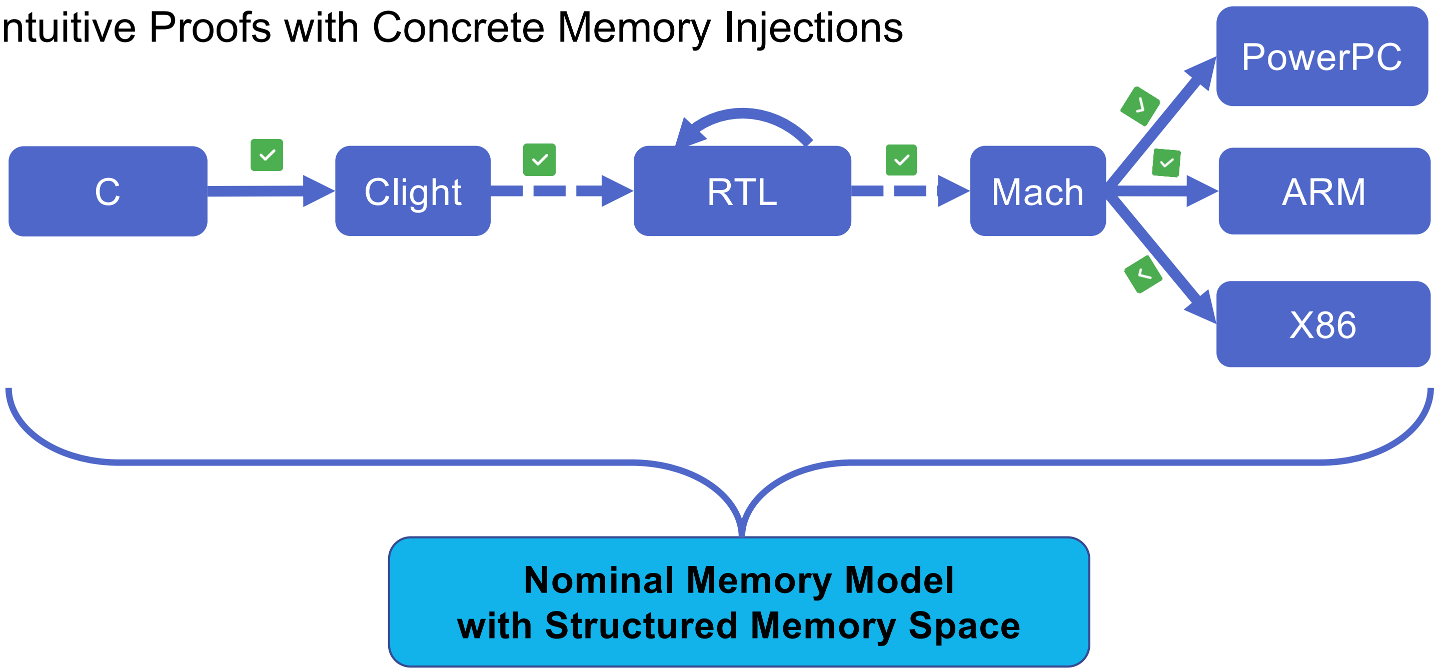

```
Variable ge : genv. (* source environment *)

Definition unchecked_meminj (b:block) :=
 match b with
  | Global _ ⇒ Some (b, 0)
  | Stack (Some id) p i ⇒
    offset ← find_frame_offset ge id i ;
    Some (Stack (Some id) p 1, offset)
 end.

Definition struct_meminj (s:sup) (b:block) :=
 if valid_block b s
 then unchecked_meminj b
 else None.
```

Nominal CompCert with Structured Memory

- **Complete Extension to Nominal CompCert with**
  - Structured Memory Space
  - Intuitive Proofs with Concrete Memory Injections

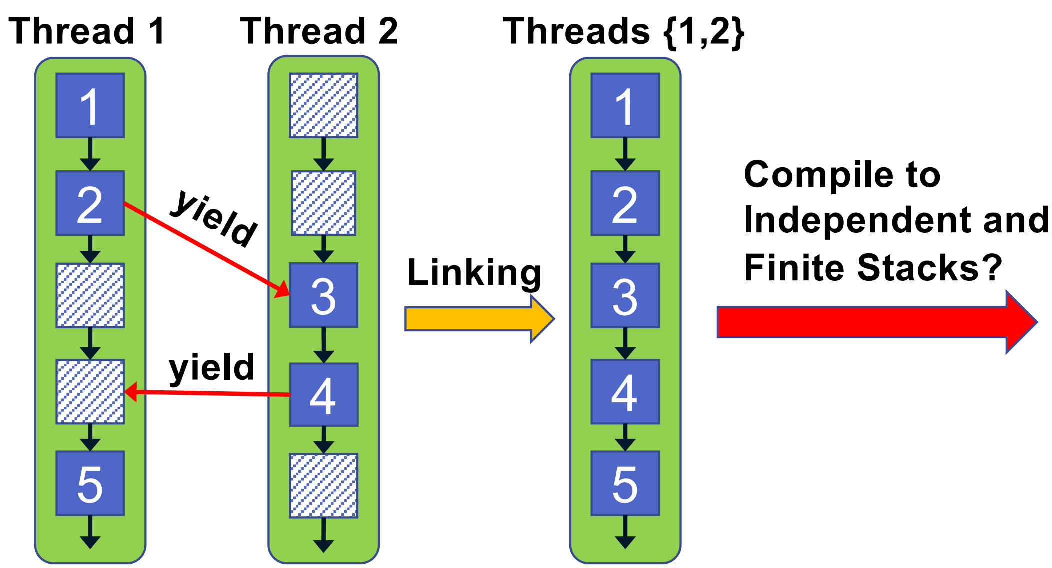


Nominal CompCert with Structured Memory

Contextual Compilation with Multiple Stacks

- **Contextual Compilation**
  - Open modules compiled in contextual memory
  - Investigated extensively for verified compilation
- **Problems with Contextual Compilation of Multiple Threads**
  1. Independent Stacks
  2. Finite and Continuous Stacks

Certified Concurrent Abstraction Layers (Gu et. al, PLDI'18)



New Approach to Support Finite Stacks

- **Background: Stack-Aware CompCert [Wang et al, POPL 2019]:**
  - First extension with a finite and contiguous stack
  - No increase of stack consumption in compilation
  - Key Technique**:** Abstract stack in the memory model

- **Observation:** Abstract stack describes properties of memory space
- **Stack-Aware Nominal CompCert**
  - Absorb the abstract stack into support:

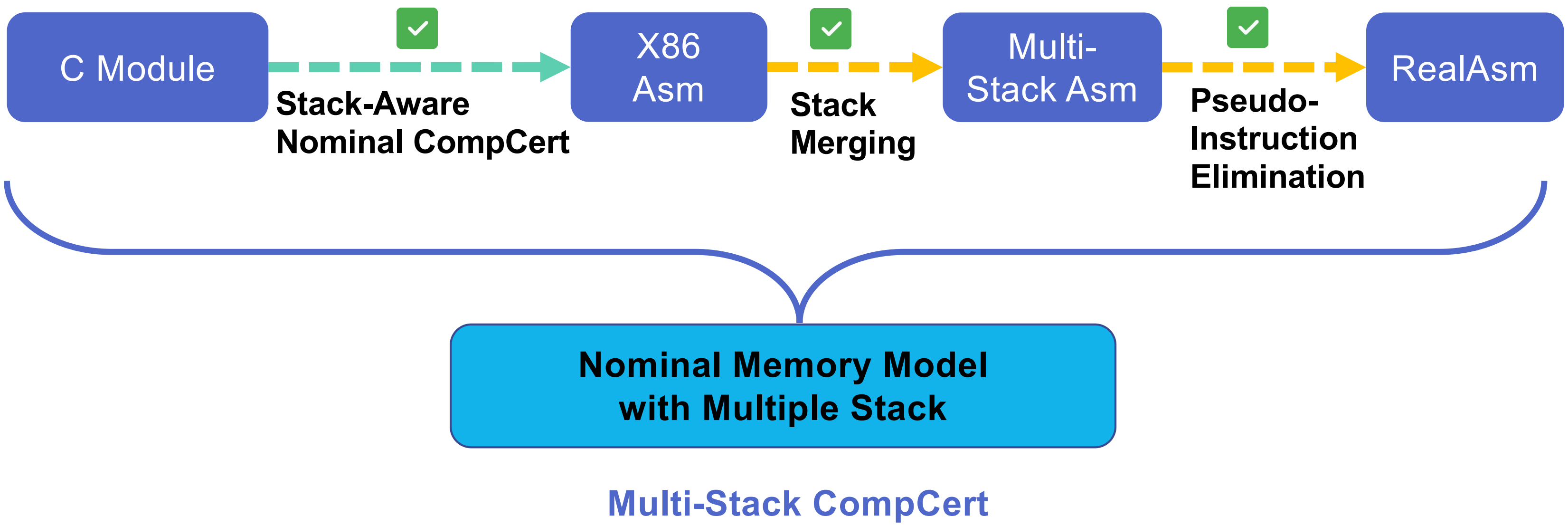
```
Record sup := {global: list ident; stack: stree; astack: stackadt}.
```

  - Significantly simplified proofs for preservation of stack consumption

Multi-Stack CompCert

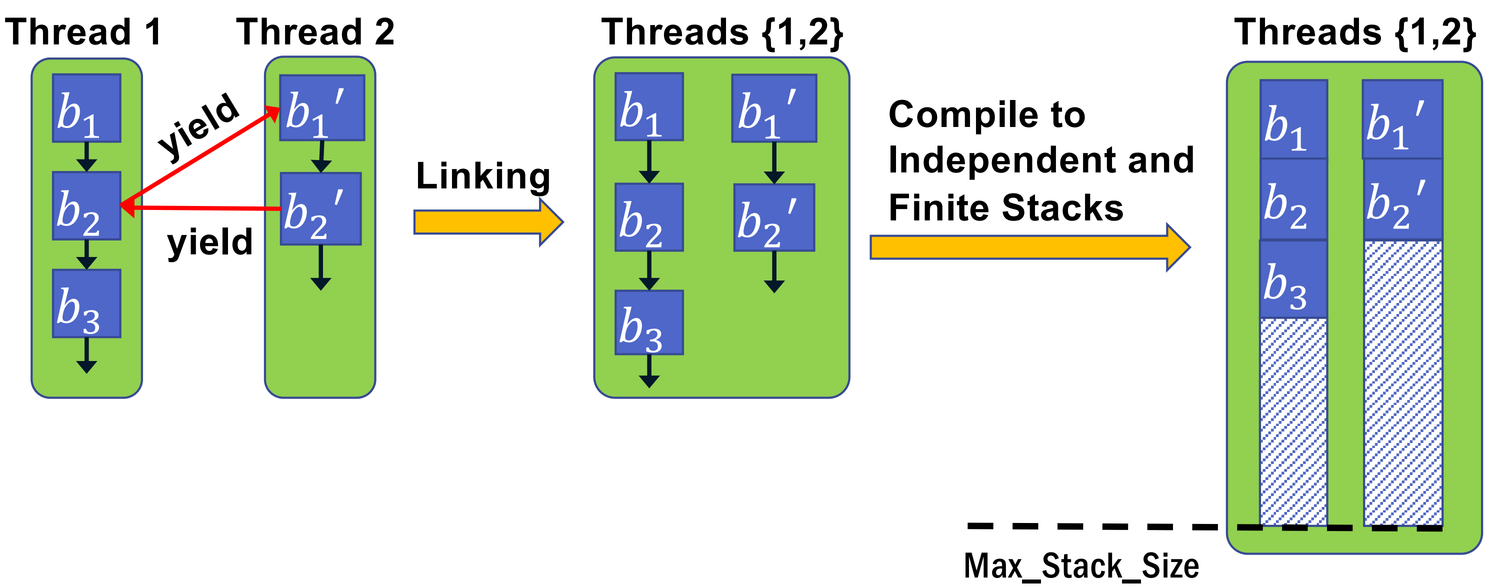
1. Merge stack frames into finite and contiguous stacks
2. Add multiple stacks that grow independently

```
Record sup := {global: list ident; stack: list stree; astack: list stackadt; thread_id: nat}.
```



Contextual Compilation to Multi-Stack Machine

- **Direct Application of Multi-Stack CompCert**



Evaluation

- **Development is based on CompCert v3.8 in Coq**
- **Nominal CompCert**
  - *Time*: 1 Person Month
  - *LOC*: 1.4K (0.5% addition to CompCert v3.8)
- **Nominal CompCert with Structured Memory Space**
  - *Time*: 2 Person Month
  - *LOC*: 3.5K (2.5% addition to Nominal CompCert)
- **Multi-Stack CompCert (including Stack-Aaware Nominal CompCert)**
  - *Time*: 3 Person Month
  - *LOC*: 15K (10.6% addition to Nominal CompCert)

- **Artifact**: https://github.com/SJTU-PLV/nominal-compcert-popl22-artifact

Conclusion

- **Nominal Memory Model**: A Principled Generalization over BBMM
- **Nominal CompCert**: A Framework for Verified Compilation of C programs
- **Principled Instantiation of Nominal CompCert**
- **Note:** Regardless the complexity of instances, the existing proofs for all the memory-injection phases remain valid.
- **Future Work:**
  - Combination of Nominal Memory Model with General Compositional Verification
  - Support for Transportation of Proofs between Different Memory Structures
  - Application to Program Verification in General