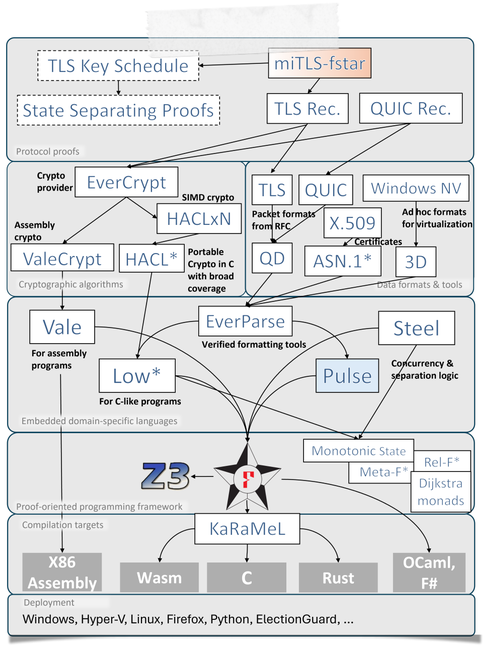
CStar: Unifying Programming and Verification in C

Di Wang
Programming Languages Lab, Peking University

2025 / 11 / 21

Towards Safer Systems Software

formal verification to the rescue?



Towards Safer Systems Software

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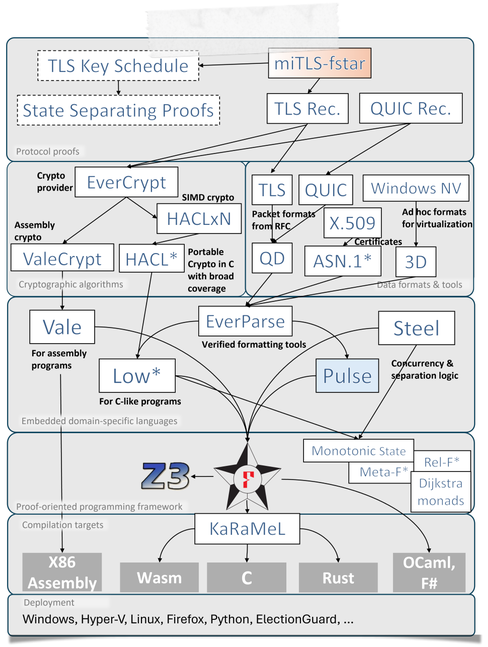
seL4
Security. Performance. Proof.

CAKEML
A Verified Implementation of ML



CertiKOS

COMPCERT

verified kernels

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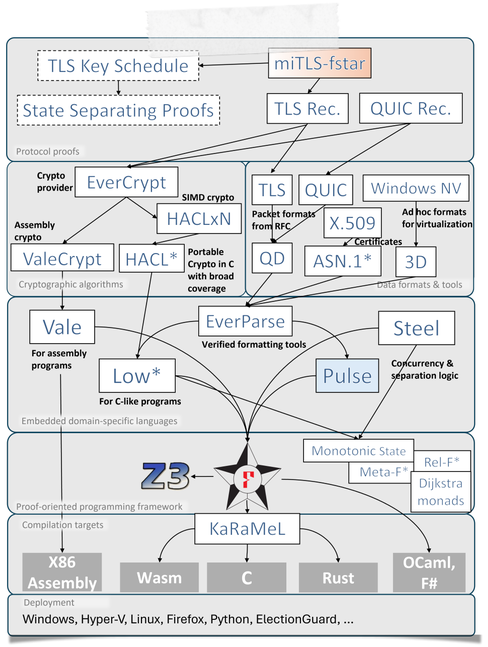

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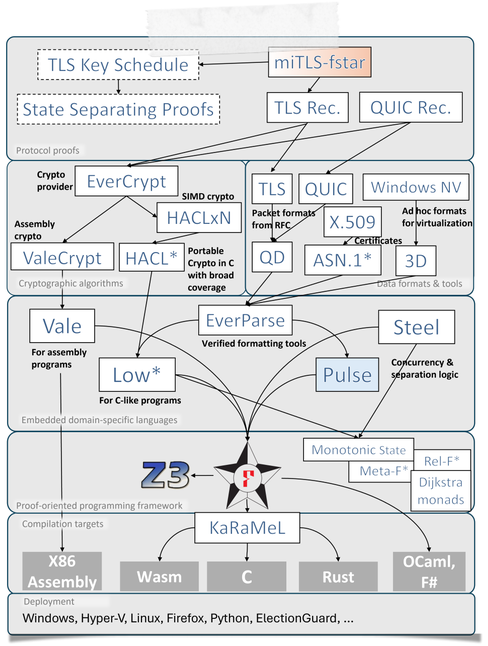

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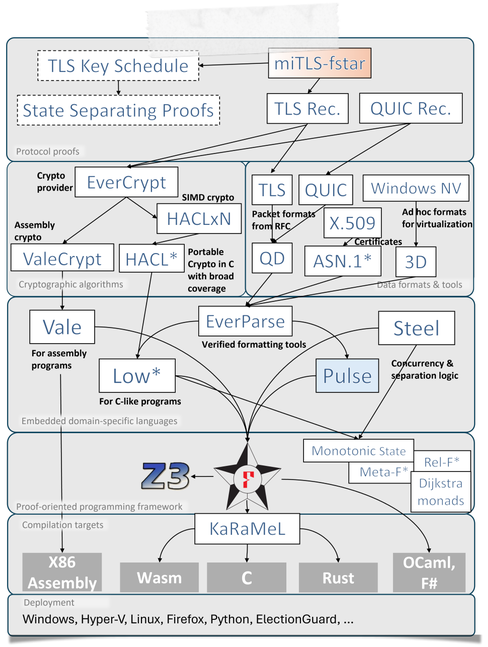

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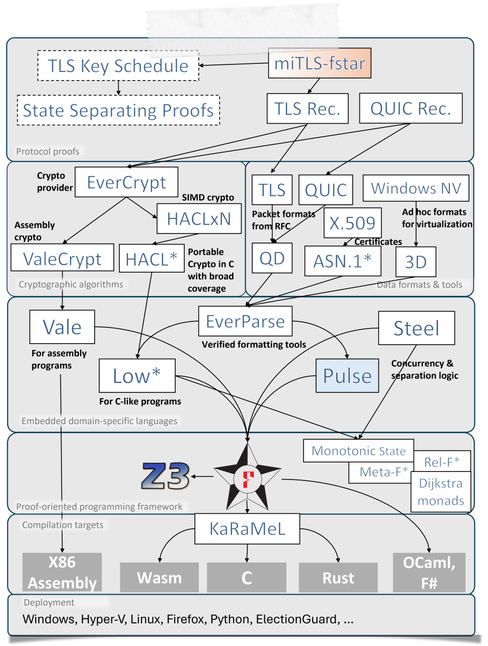

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Dafny
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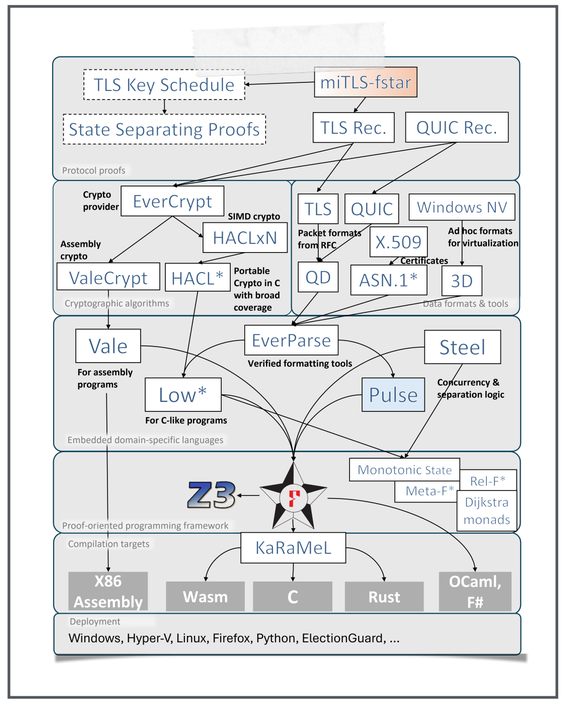

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"theorem prover" sounds scary

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Language Enhancement?

let us focus on C & Rust

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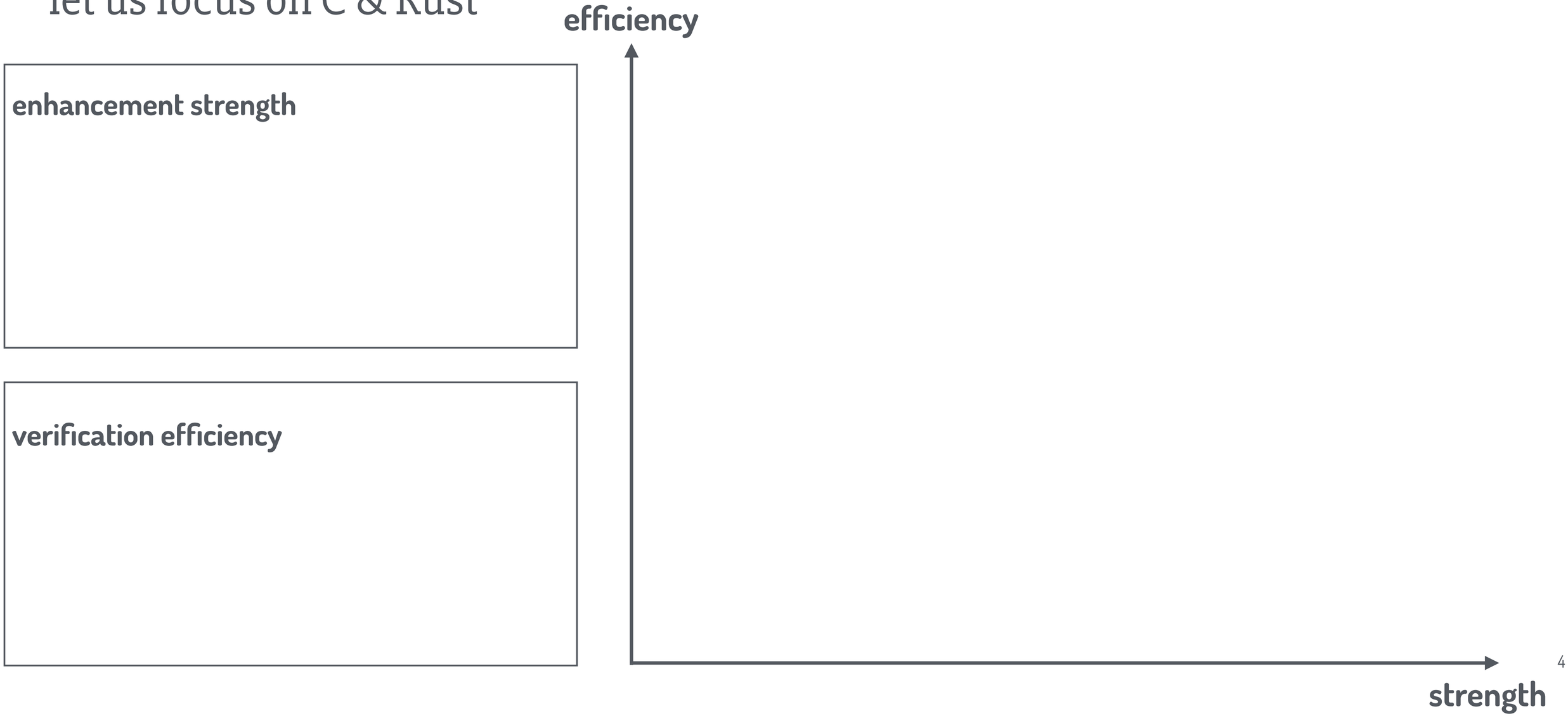

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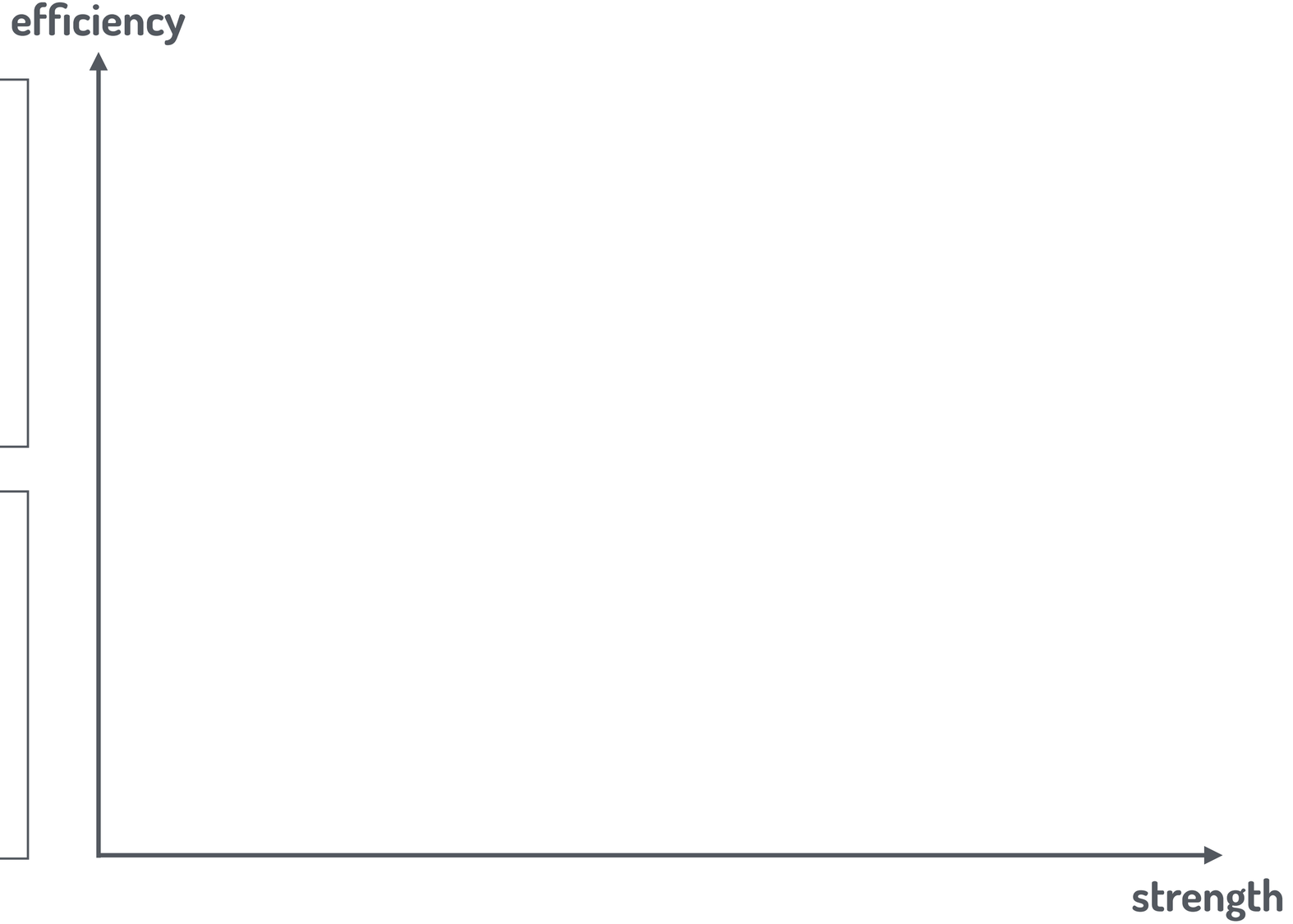
enhancement strength

- verified properties: memory / thread safety, functional correctness, security, ...

verification efficiency



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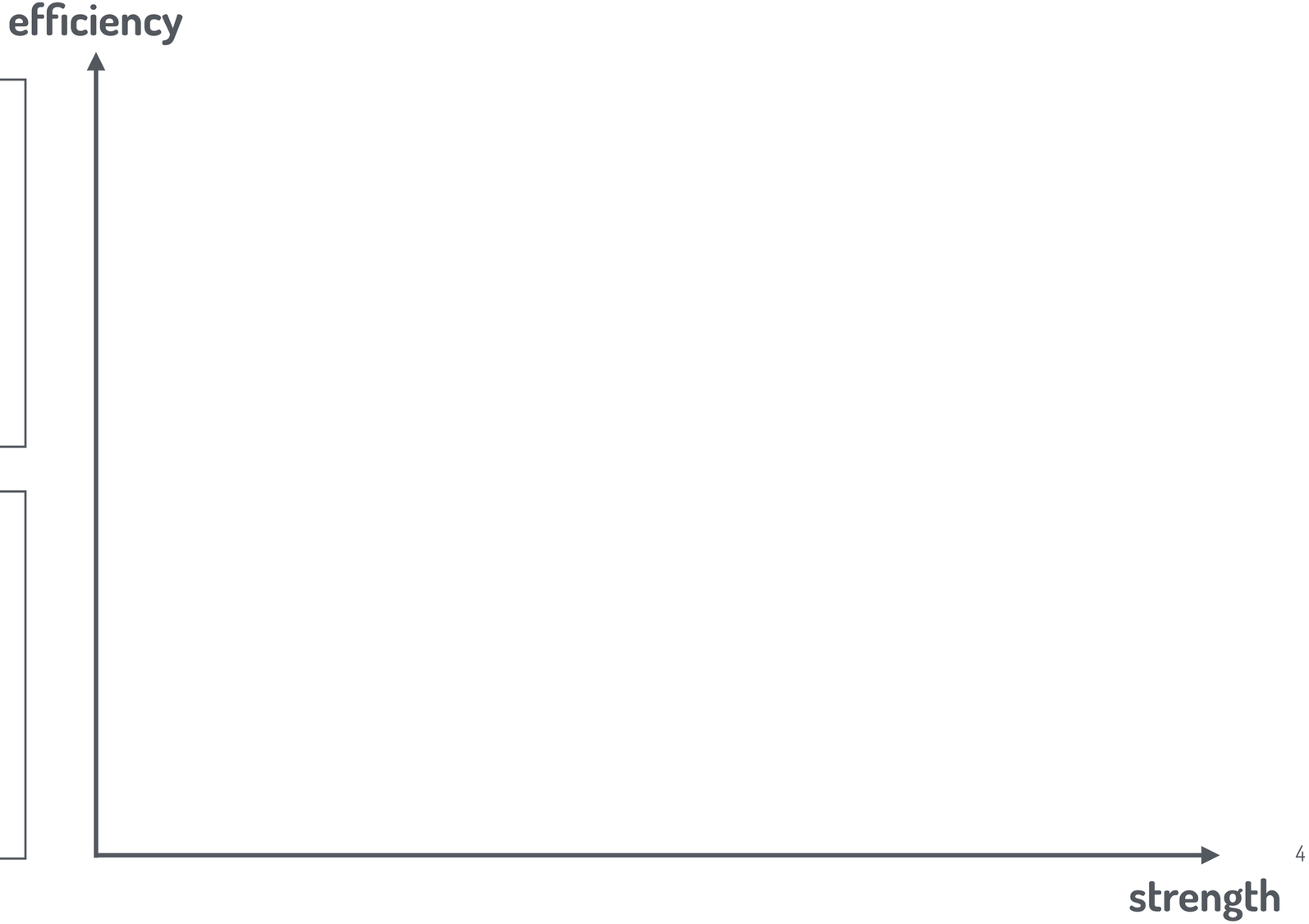

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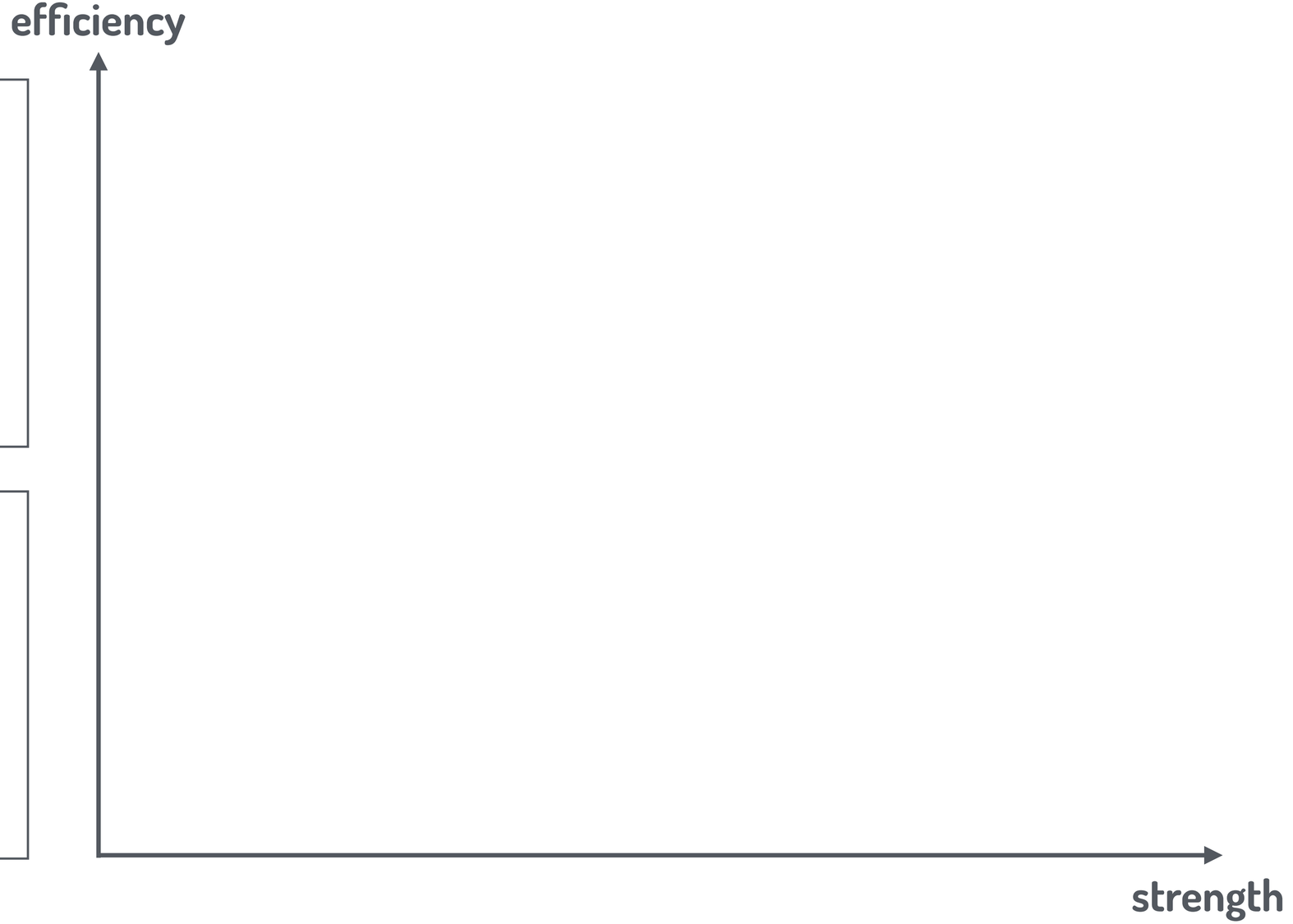

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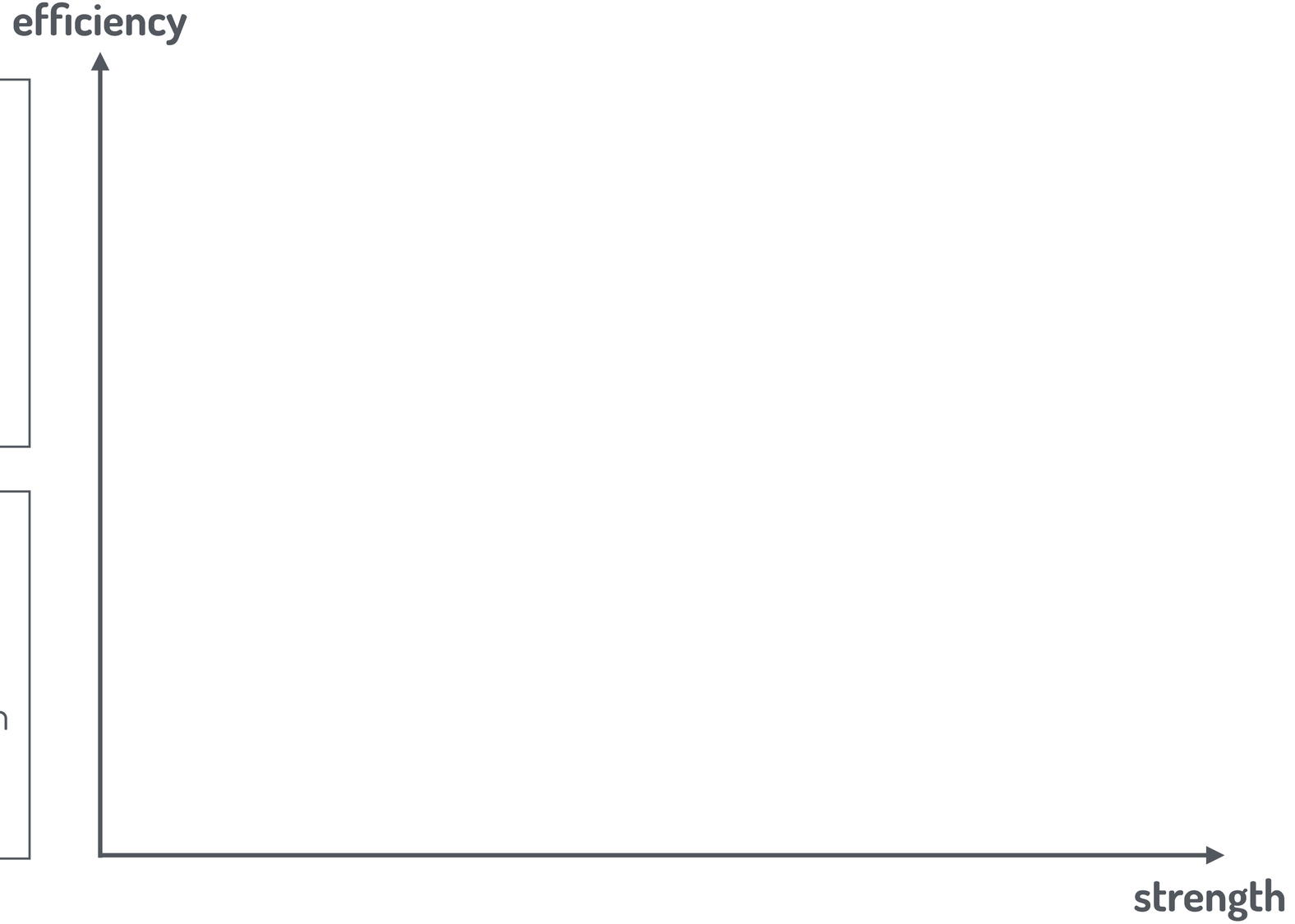

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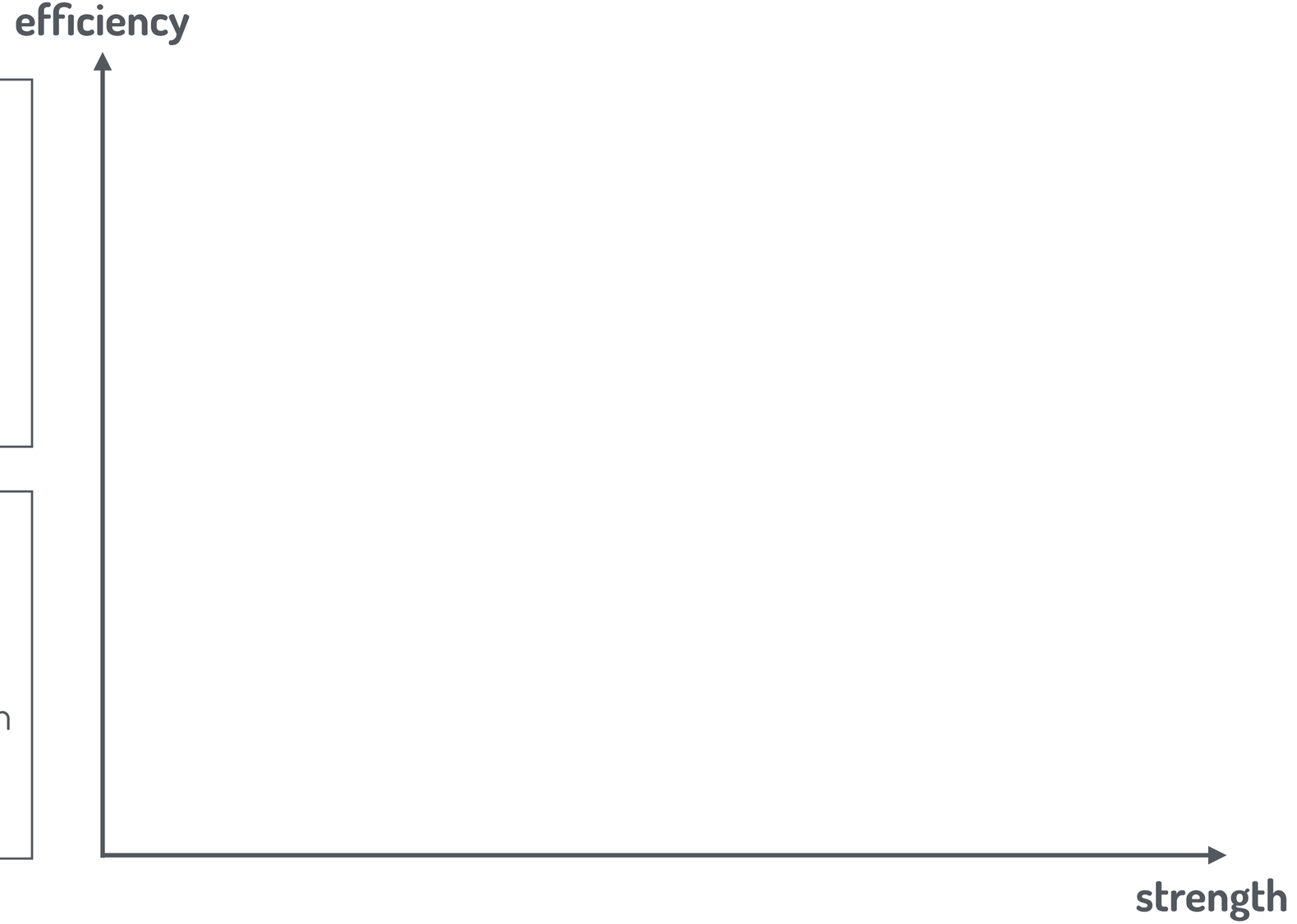

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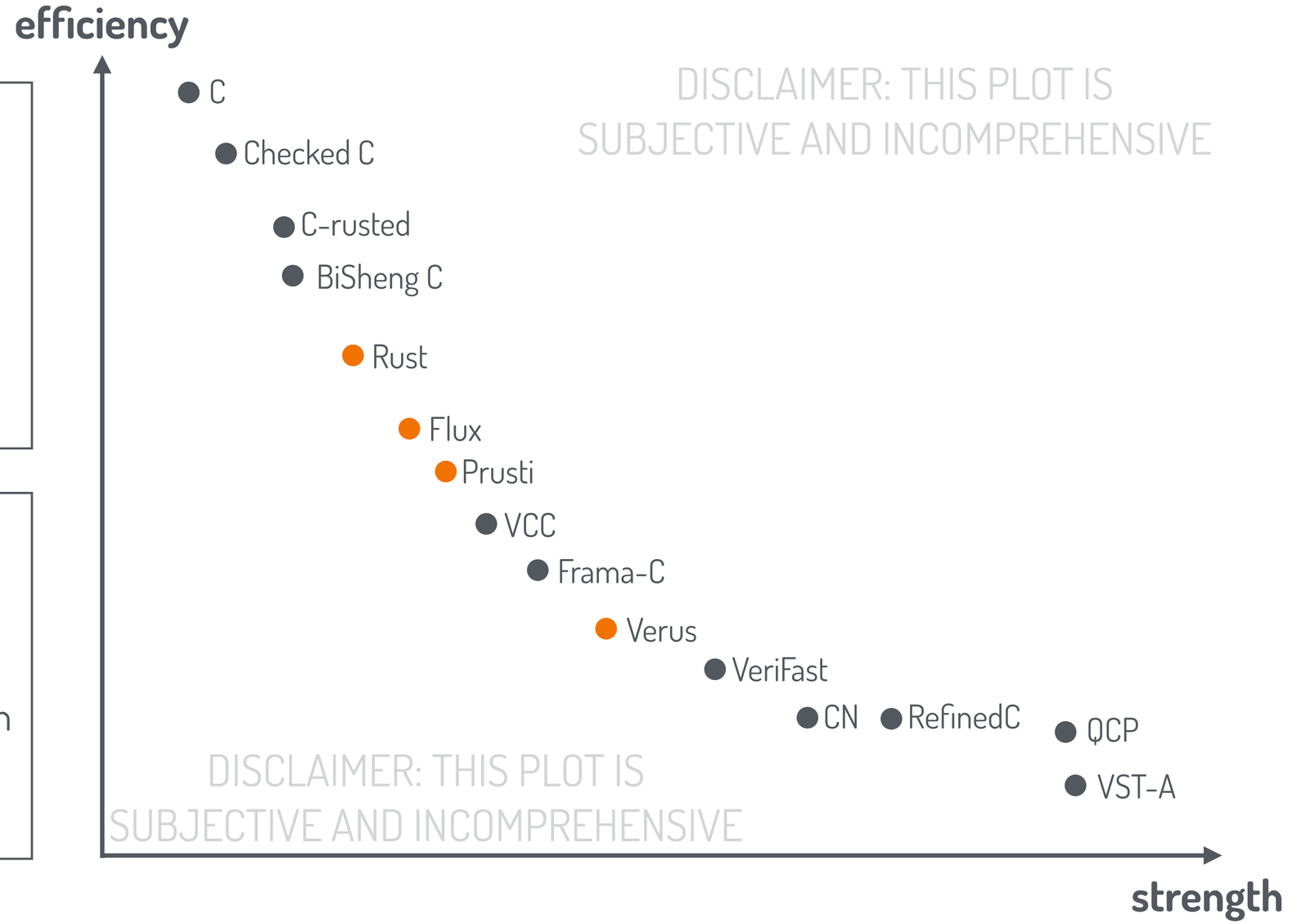
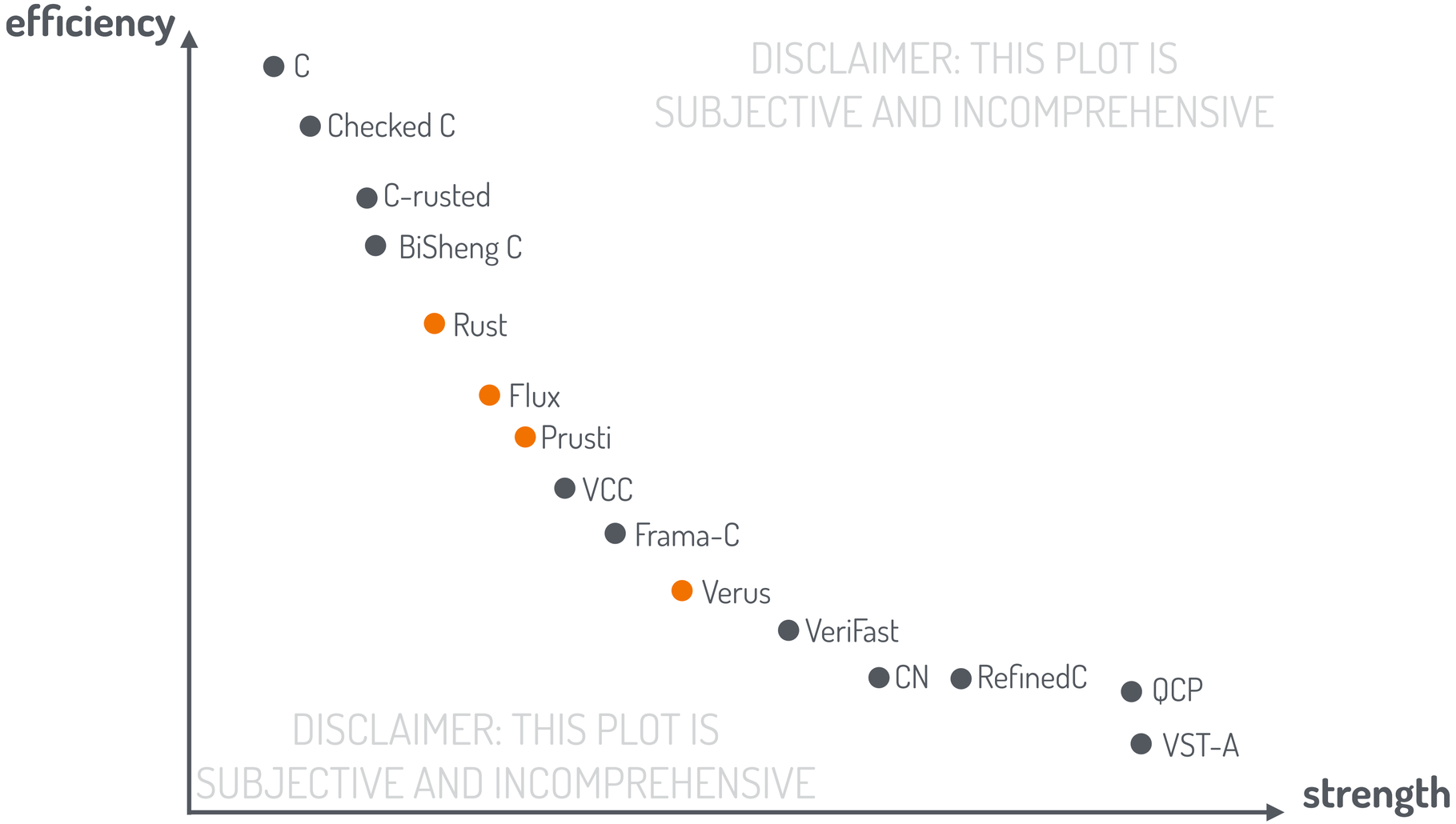


DISCLAIMER: THIS PLOT IS SUBJECTIVE AND INCOMPREHENSIVE

Obs I: VC Generation is Required

if aiming for high efficiency



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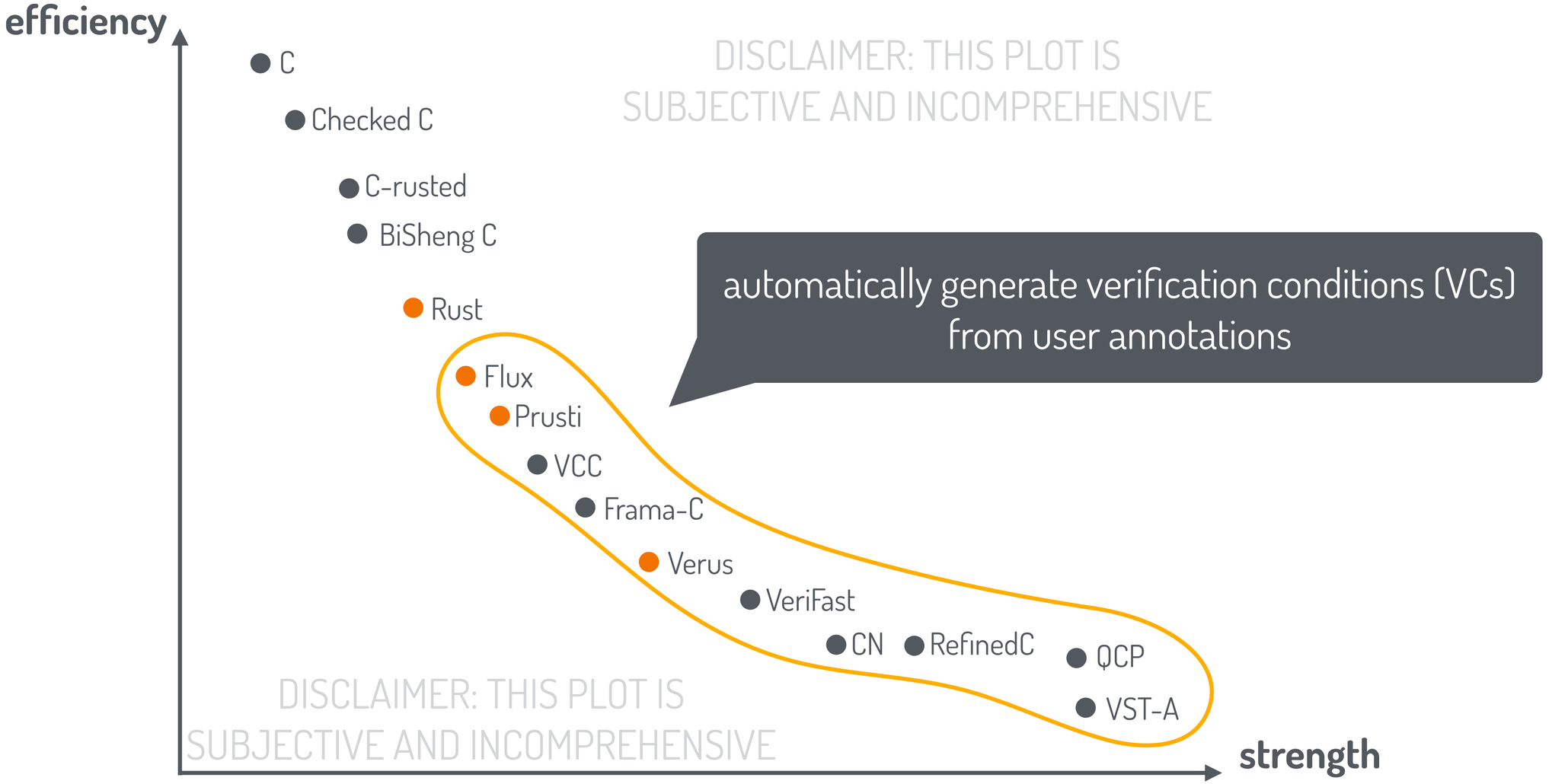

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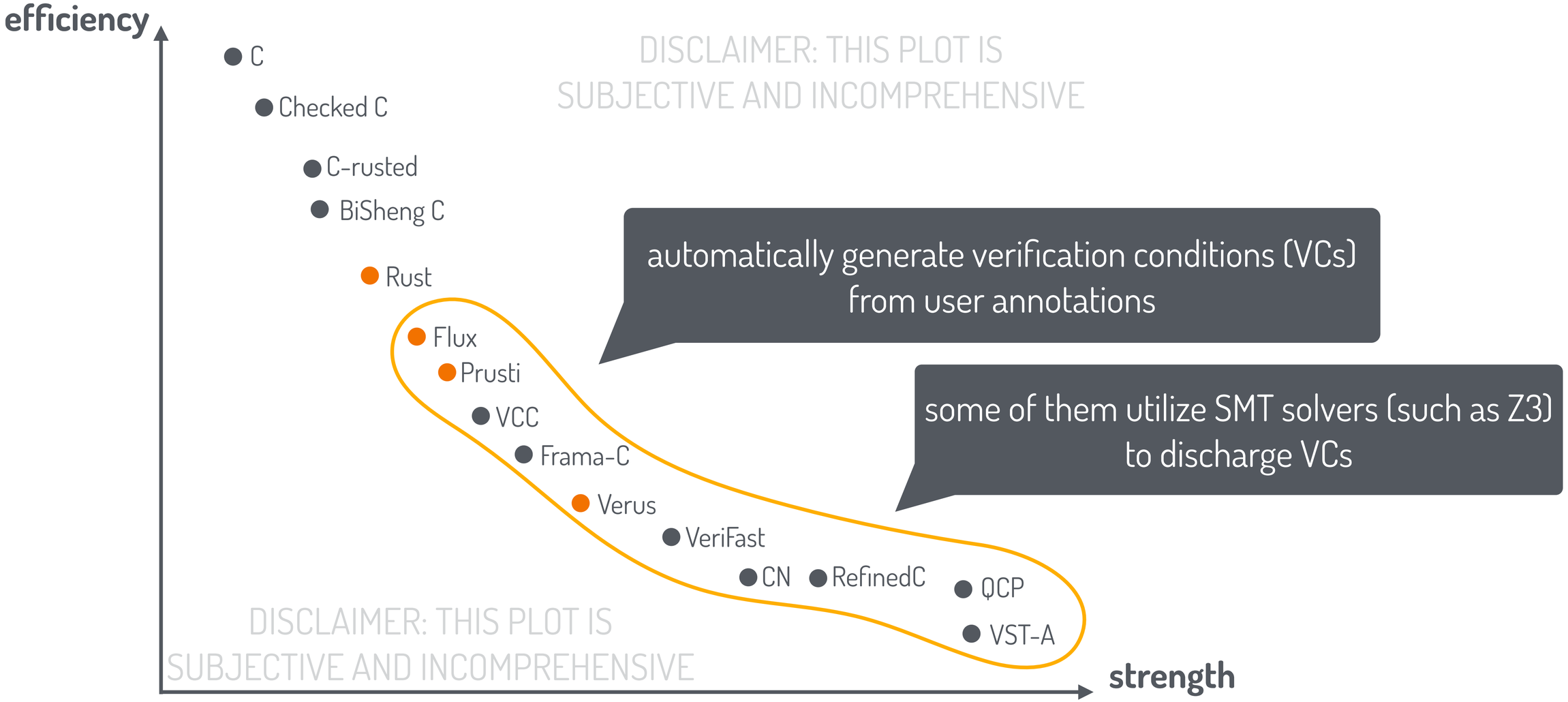
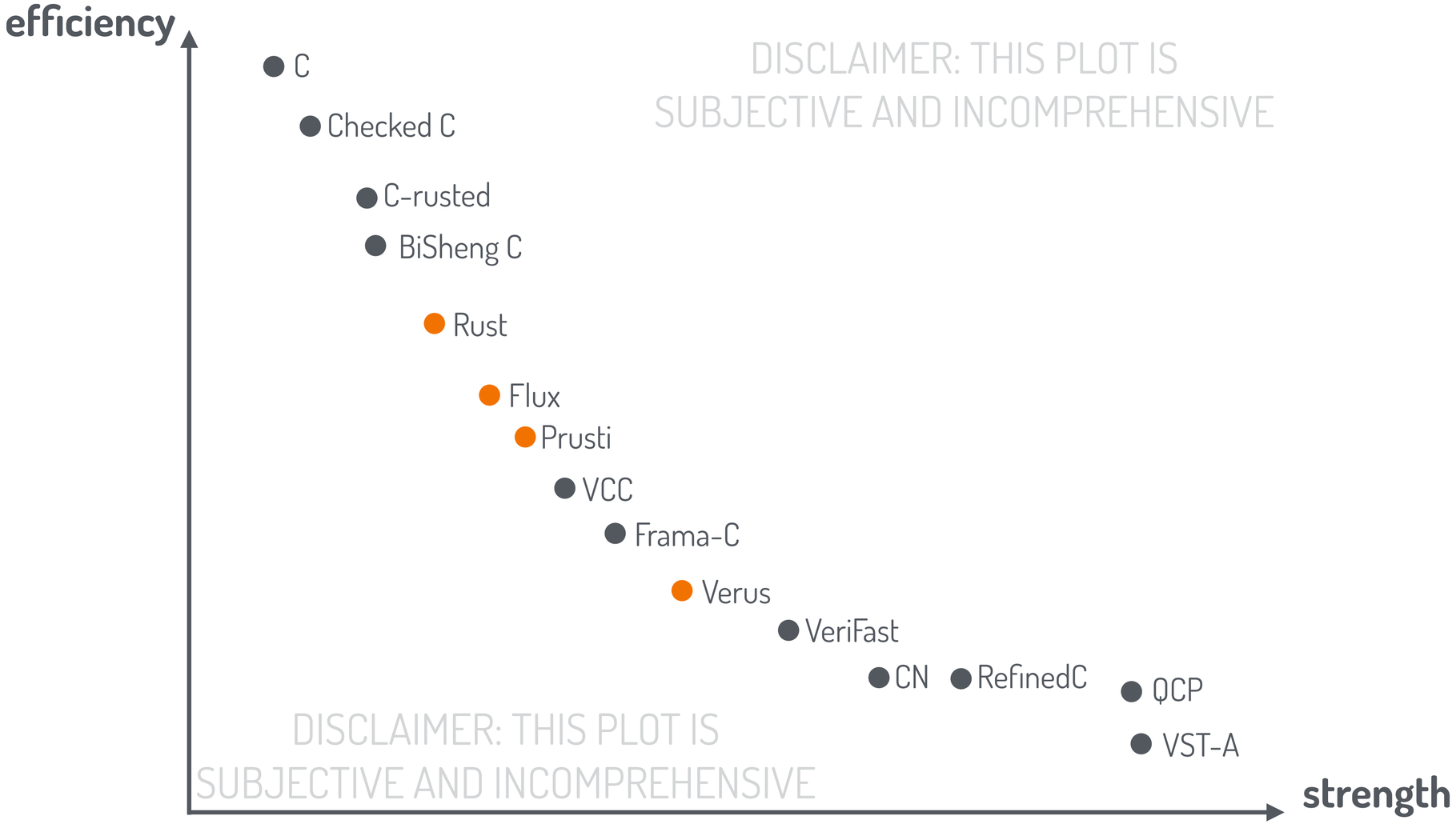


CStar Demo: VC Generation

nothing new yet

Obs: Manual Proof is Unavoidable

if aiming at strong strength



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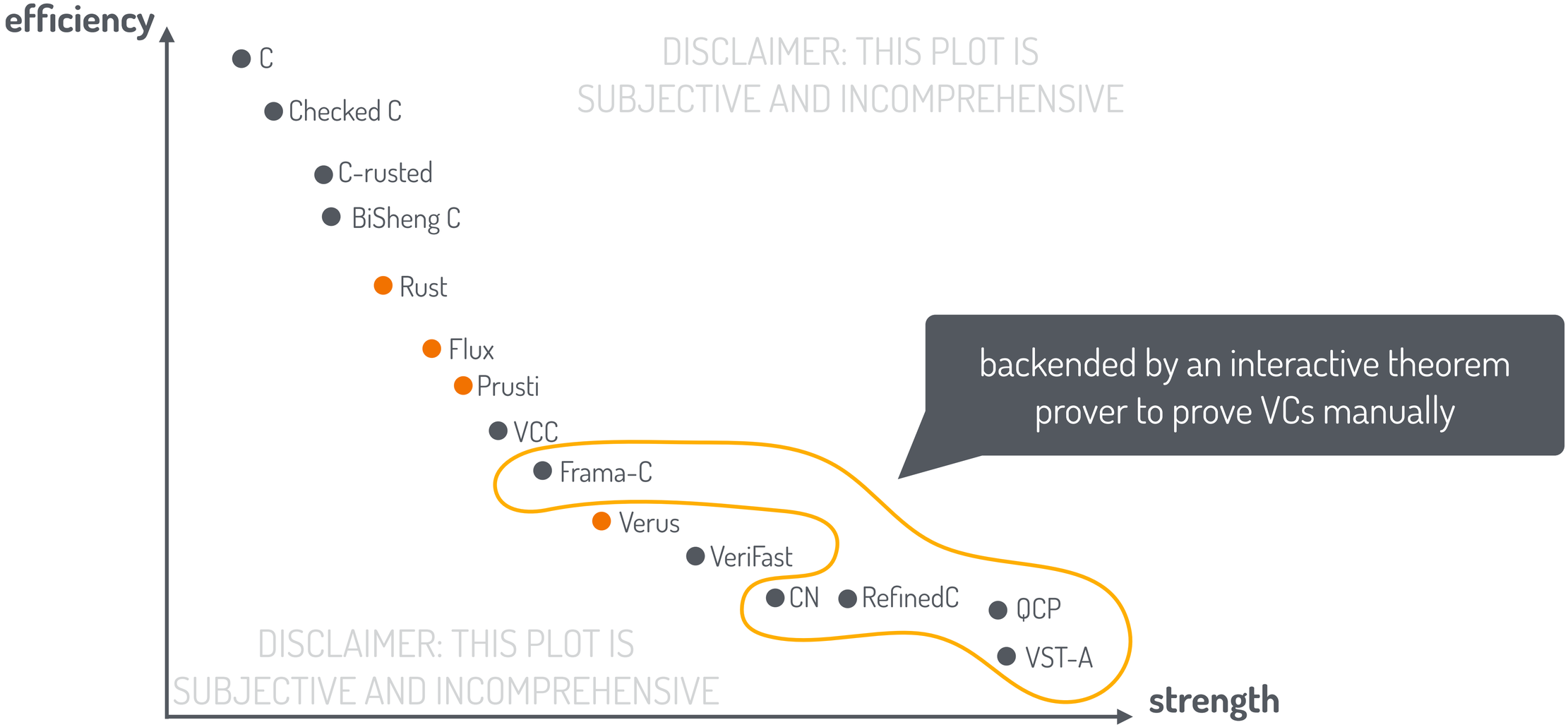

Prob I: Proof Encapsulation

theorem provers are nice, but ...

current status in CN (and many others):
proofs are delegated to Rocq

```
lemma append_nil (datatype seq l1)
  requires true;
  ensures append(l1, Nil {}) == l1;

lemma append_cons (datatype seq l1, i32 x, datatype seq l2)
  requires true;
  ensures append(l1, Cons {head: x, tail: l2})
          == append(snoc(l1, x), l2);
```

```
struct node *tmp = cur->tail;
cur->tail = last;
last = cur;
cur = tmp;
/*@ unfold rev(L2); @*/
/*@ apply append_cons (rev (tl(L2)), hd(L2), L1); @*/
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principle: integrate **proof-specification-implementation** together into one language

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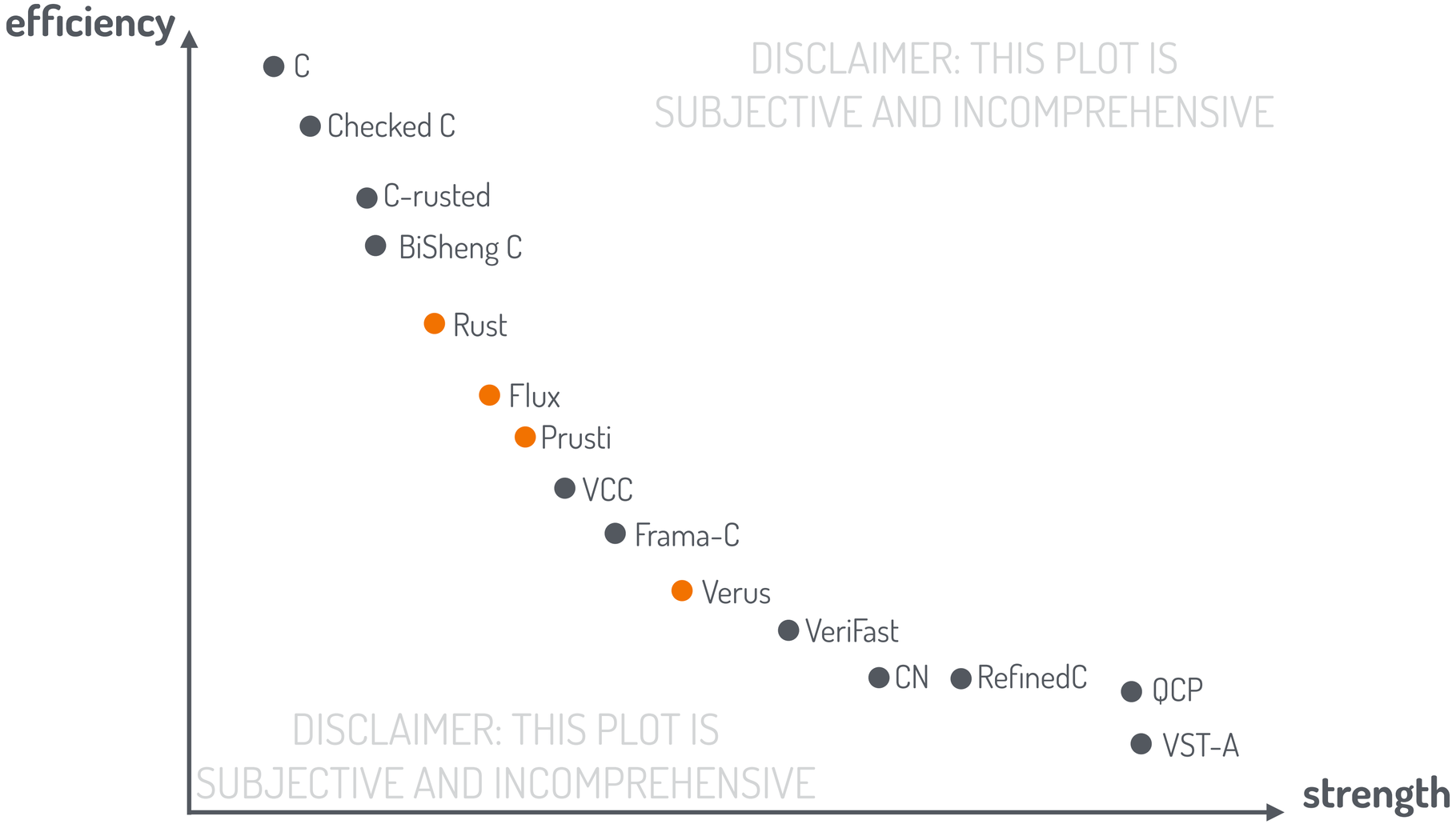

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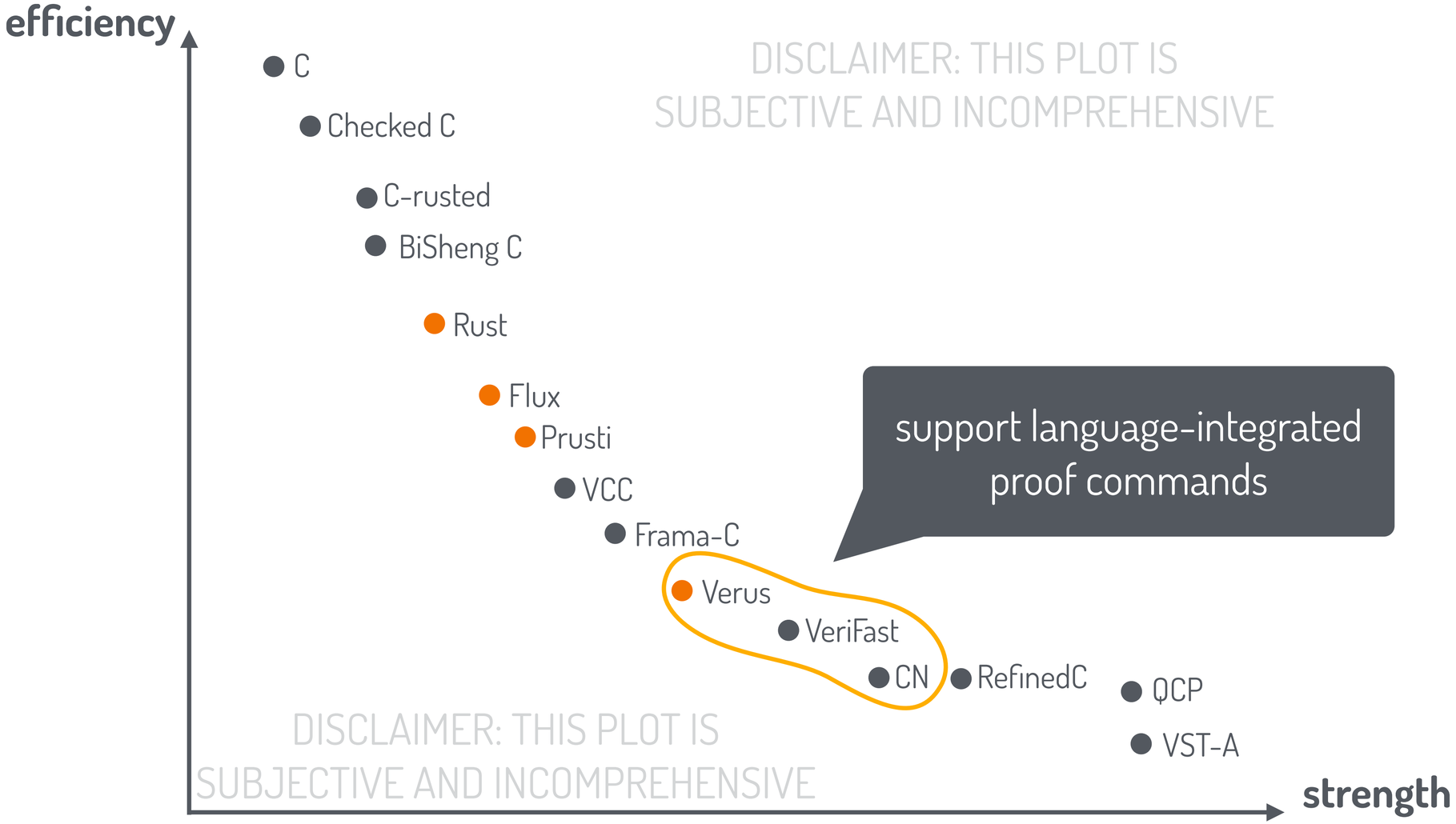

```
struct node *reverse(struct node *xs)
/*@ requires take L = IntList(xs);
    ensures  take L_ = IntList(return);
             L_ == rev(L);
@*/
{

  struct node *last = 0;
  struct node *cur = xs;
  /*@ apply append_nil(rev(L)); @*/
  while(1)
  /*@ inv take L1 = IntList(last);
          take L2 = IntList(cur);
          append(rev(L2), L1) == rev(L);
  @*/
  {
    if (cur == 0) {
      /*@ unfold rev(Nil {}); @*/
      /*@ unfold append(Nil {}, L1); @*/

      return last;
    }
    struct node *tmp = cur->tail;
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example program with proof commands in CN

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example program with proof commands in CN

```
public boolean remove(Object o)
/*: requires " init"
    modifies content, csize
    ensures
 "( result  → (∃ i. (i,o)∈old content ∧
          (¬∃ j. j<i ∧ (j,o)∈old content) ∧
          (∀ j e. 0≤j∧j<i→(j,e)∈content=(j,e)∈old content) ∧
          (i≤j∧j<csize→(j,e)∈content=(j+1,e)∈old content)) ∧
  (¬result → (content=old content∧¬∃i. (i,o)∈old content))" */
{
 int index = 0;
 while /*: inv "(∀j. 0≤j∧j<index→o≠elements.[j]) ∧
                0≤index ∧ size=old size" */
       (index < size) {
  if (elements[index] == o) {
   shift (index);
   /*: note ObjectRemoved:
    "∀j e. (0≤j∧j<index→(j,e)∈content=(j,e)∈old content) ∧
       (index≤j∧j<csize→(j,e)∈content=(j+1,e)∈old content)"
            from shift_Postcondition , LoopInv, LoopCondition
                                        content_def , csize_def ;
       witness index for
    "∃i. (i,o)∈old content ∧ (¬∃j. j<i ∧ (j,o)∈old content) ∧
      (∀j e. (0≤j∧j<i→(j,e)∈content=(j,e)∈old content) ∧
       (i≤j∧j<csize→(j,e)∈content=(j+1,e)∈old content))" */
   return true;
  }
  index = index + 1;
 }
 return false ;
}
```

example program with proof commands in Jahob

Prob II: Programmable Proof

proof commands are nice, but ...

$$
\begin{array}{lcl}
p & ::= & p_1 \,;\, p_2 \\
 & | & \text{assert } l\text{: } F \text{ from } \vec{h} \\
 & | & \text{note } l\text{:}F \text{ from } \vec{h} \\
 & | & \text{localize in } (p \,;\, \text{note } l\text{:}F) \\
 & | & \text{mp } l\text{:}(F \rightarrow G) \\
 & | & \text{assuming } l_F\text{:}F \text{ in } (p \,;\, \text{note } l_G\text{:}G) \\
 & | & \text{cases } \vec{F} \text{ for } l\text{:}G \\
 & | & \text{showedCase } i \text{ of } l : F_1 \vee \ldots \vee F_n \\
 & | & \text{byContradiction } l\text{:}F \text{ in } p \\
 & | & \text{contradiction } l\text{:}F \\
 & | & \text{instantiate } l\text{:}\forall \vec{x}.F \text{ with } \vec{t} \\
 & | & \text{witness } \vec{t} \text{ for } l\text{:}\exists \vec{x}.F \\
 & | & \text{pickWitness } \vec{x} \text{ for } l_F\text{:}F \text{ in } (p \,;\, \text{note } l_G\text{:}G) \\
 & | & \text{pickAny } \vec{x} \text{ in } (p \,;\, \text{note } l\text{:}F) \\
 & | & \text{induct } l\text{:}F \text{ over } n \text{ in } p
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integrated proof commands in Jahob

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integrated proof commands in Jahob

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principle: support using the full language to **programmatically** construct proof

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The LCF Solution

logic for computable functions

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- the **LCF architecture** for theorem proving by Robin Milner in the 1970s

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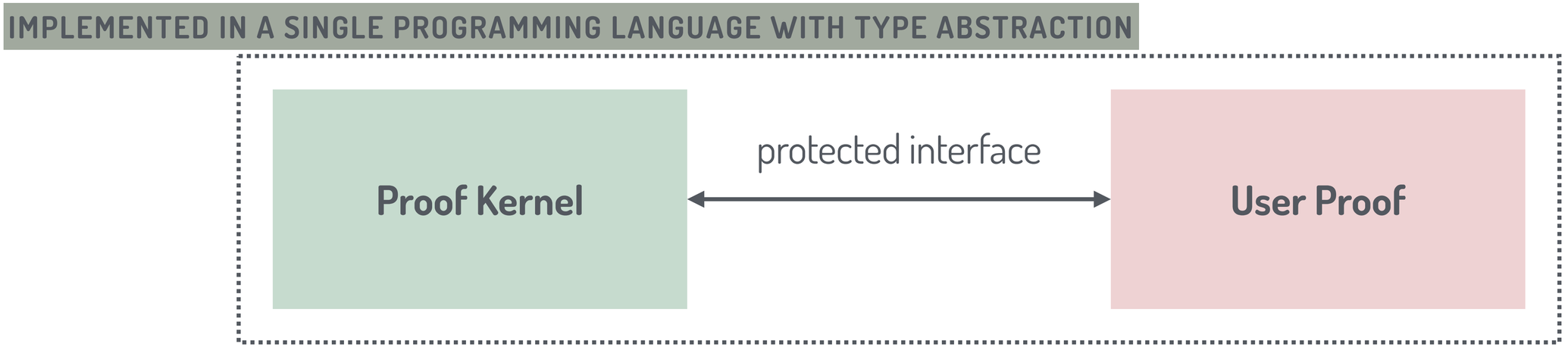
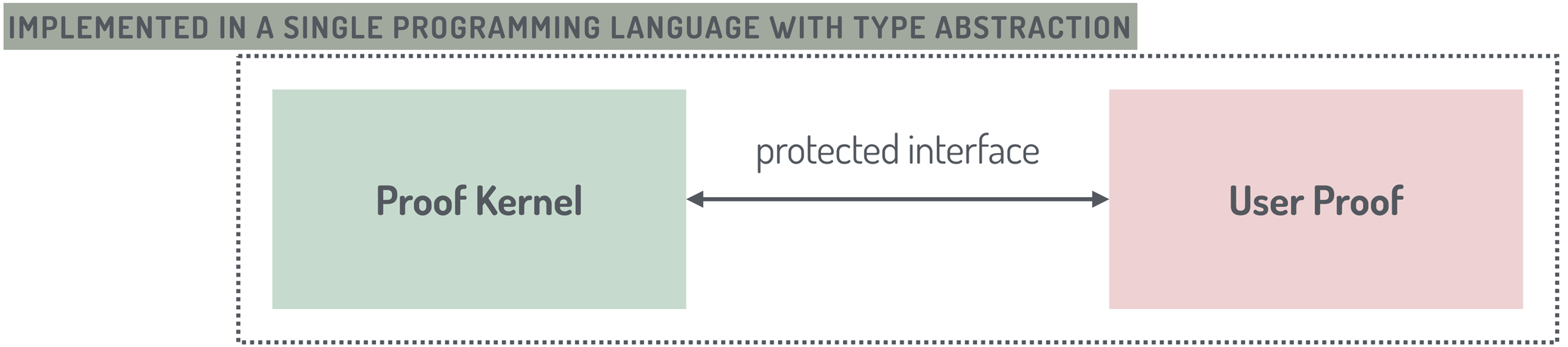
- programming formal proof is to **compute theorems** using a **protected interface**



The LCF Solution

logic for computable functions

- the **LCF architecture** for theorem proving by Robin Milner in the 1970s
- programming formal proof is to **compute theorems** using a **protected interface**
- **correct-by-construction** even when extended with arbitrary user proof code



CStar Demo: Proof Programming

a practice of LCF in C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1898

it is now already possible to prove VCs in C

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but we can do better by introducing
program-proof states

CStar Demo: Program-Proof State

essentially, a symbolic representation of the program state


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a VC is a prop "pre |-- post" at a program point

both are program-proof states

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proving a VC is coupled with programming in CStar

both are program-proof states

a VC is a prop "pre |-- post" at a program point

proving a VC is coupled with programming in CStar
you write a proof to transform from pre to post

CStar Demo: Program Proof

unify program and proof

The Architecture of CStar

how to ensure correct-by-construction

The Architecture of CStar

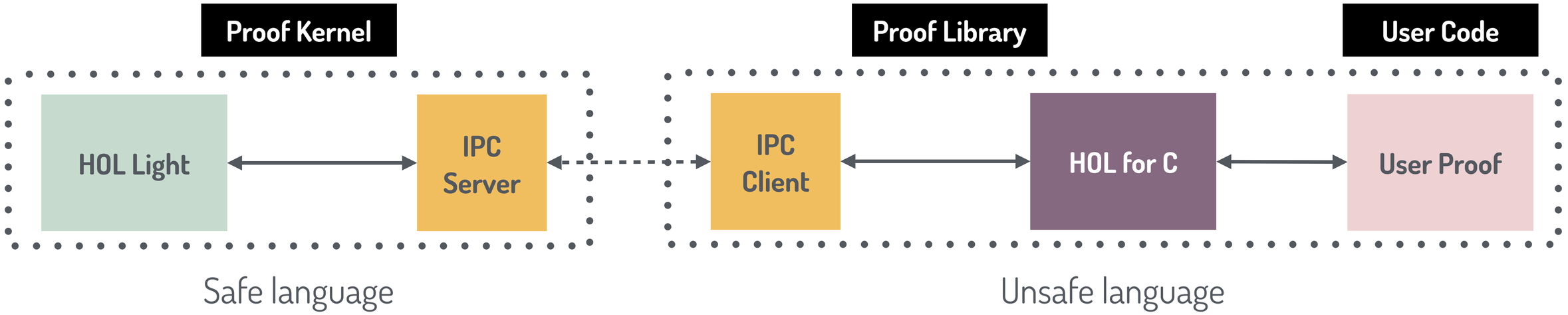
how to ensure correct-by-construction

- the original LCF design heavily relies on **type abstraction** provided by the ML language

The Architecture of CStar

how to ensure correct-by-construction

- the original LCF design heavily relies on **type abstraction** provided by the ML language
- we worked out a **language-agnostic** variant of the LCF-architecture with **process separation**



The Architecture of CStar

how to maintain the program-proof states

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QCP: A Practical Separation Logic-based C Program Verification Tool

Xiwei Wu[1], Yueyang Feng[1,*], Xiaoyang Lu[1,*], Tianchuan Lin[1], Kan Liu[1], Zhiyi Wang[2], Shushu Wu[1], Lihan Xie[1], Chengxi Yang[1], Hongyi Zhong[1], Naijun Zhan[2], Zhenjiang Hu[2], and Qinxiang Cao[1,†]

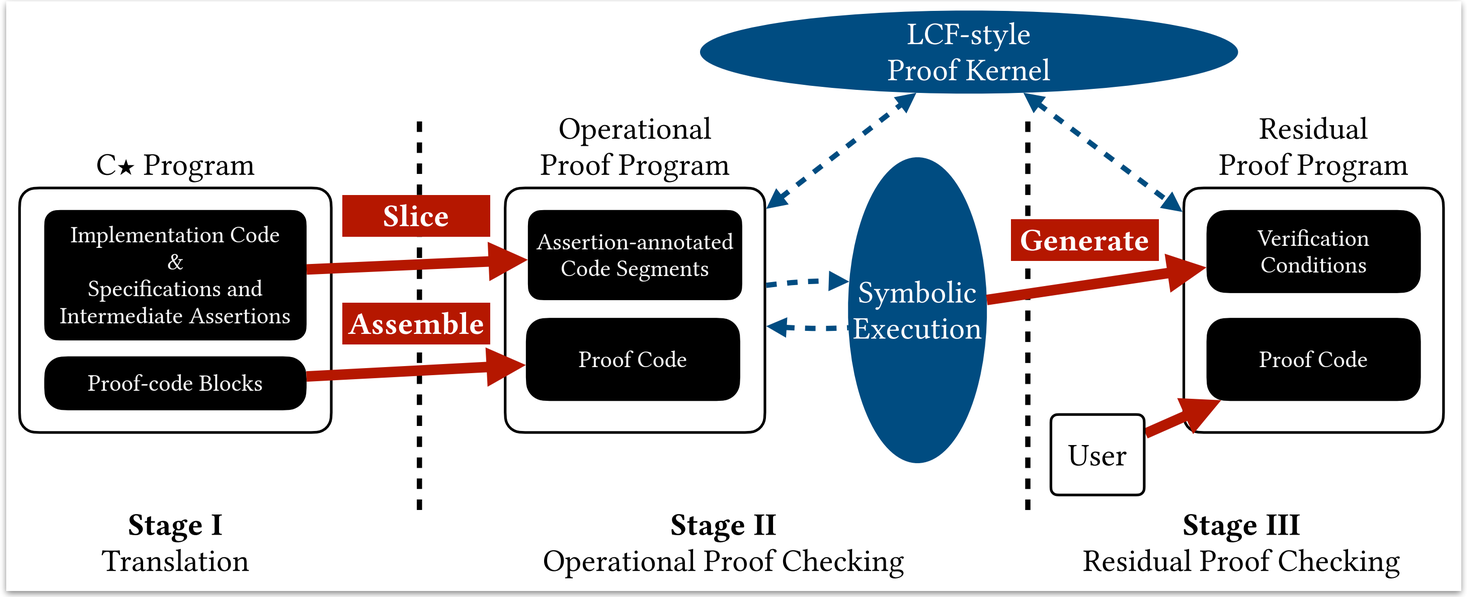
[1] Shanghai Jiao Tong University
{yashen, fyyvexoben, luxy1115, caoqinxiang}@sjtu.edu.cn
[2] Peking University
2301111964@stu.pku.edu.cn

https://arxiv.org/pdf/2505.12878

The Architecture of CStar

how to maintain the program-proof states

- compute symbolic heap information via **forward symbolic execution**
- CStar now employs (but is largely **agnostic** of) QCP's symbolic executor for **separation-logic** reasoning
- QCP evolves the program-proof states for program code; CStar evolves the program-proof states for proof code



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users can now use the full power of C
to conduct proof and verification

CStar Demo: Tactics

all implemented outside the proof kernel

CStar Demo: SMT Integration

achieve controllable automation

CStar Demo: Proof Encapsulation

one can implement program-proof libraries

CStar

Unifying Programming and Verification in C

CStar

Unifying Programming and Verification in C

prob i: proof encapsulation

CStar

Unifying Programming and Verification in C

prob i: proof encapsulation

prob ii: programmable proof

CStar

Unifying Programming and Verification in C

principle i: integrate **proof-specification-implementation** together into one language

prob i: proof encapsulation

prob ii: programmable proof

CStar

Unifying Programming and Verification in C

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CStar

Unifying Programming and Verification in C

principle i: integrate **proof-specification-implementation** together into one language

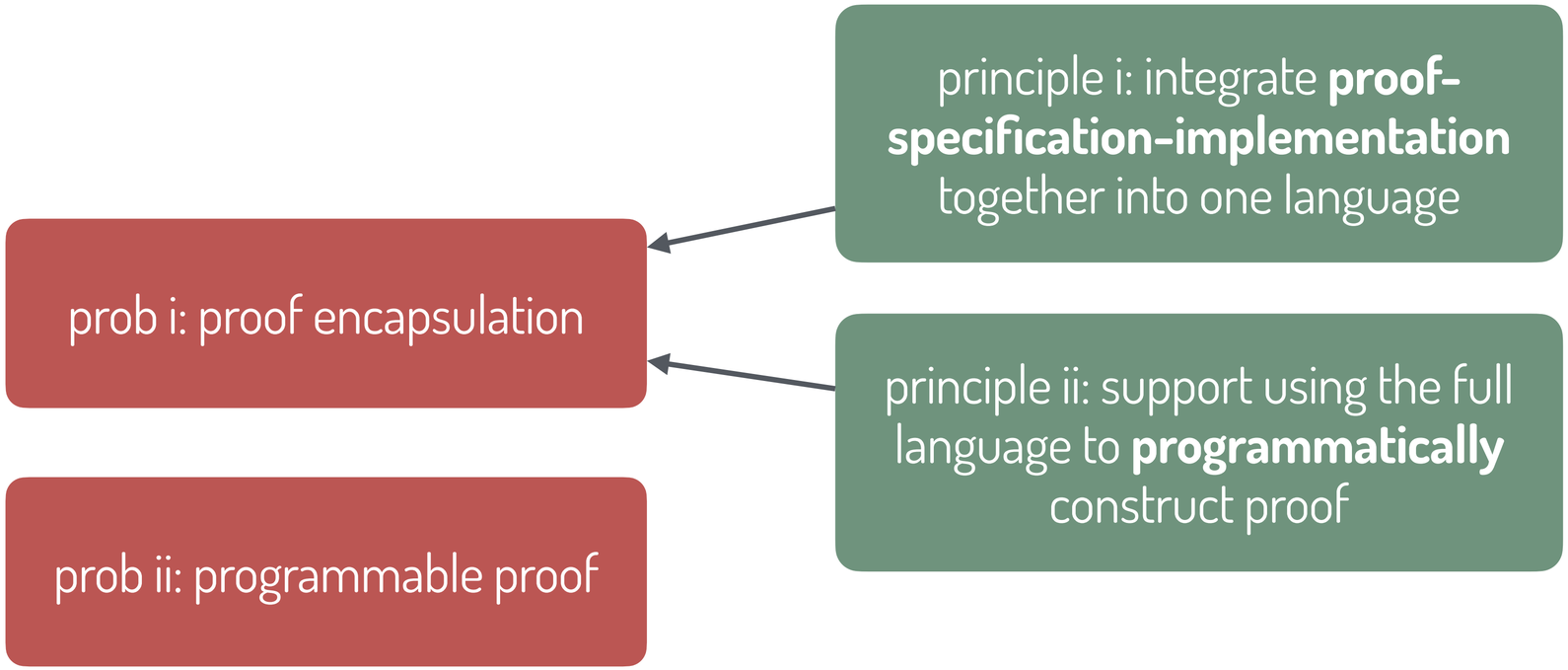
principle ii: support using the full language to **programmatically** construct proof

prob i: proof encapsulation

prob ii: programmable proof

CStar

Unifying Programming and Verification in C



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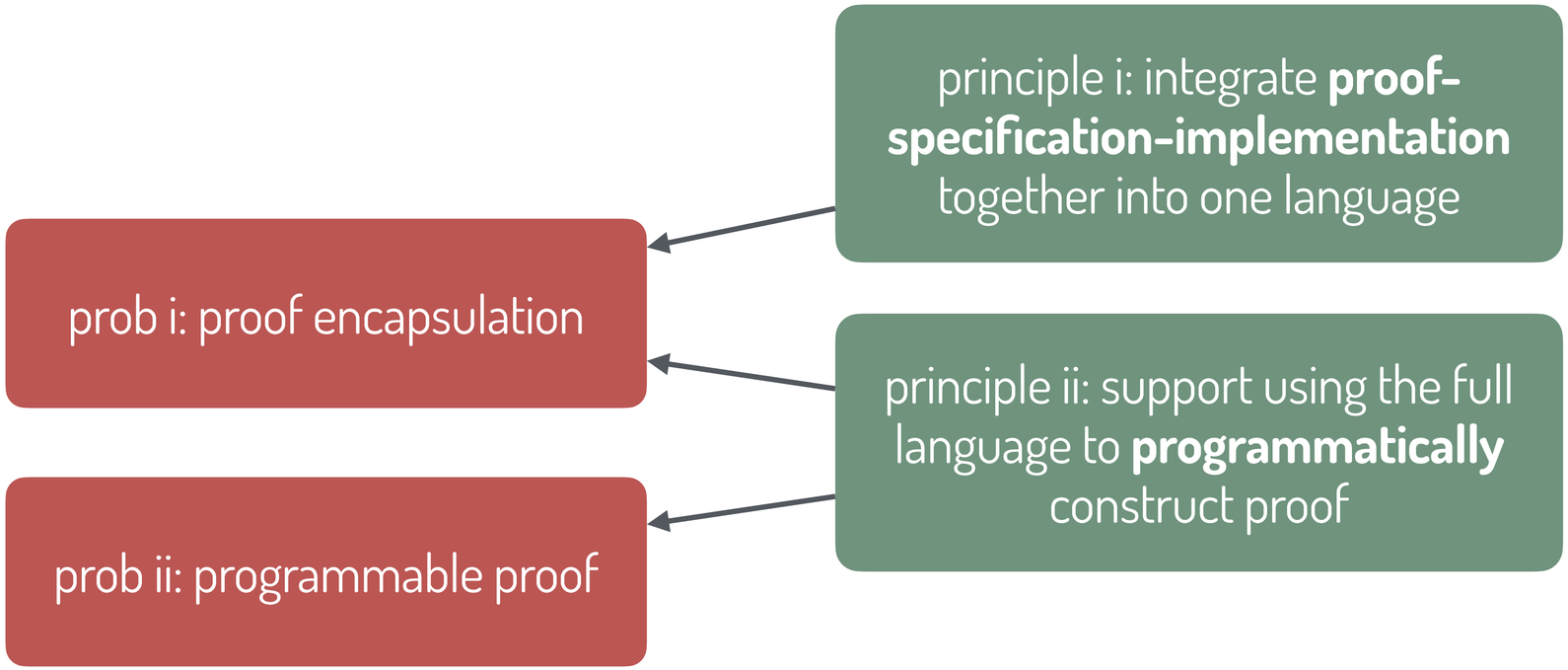

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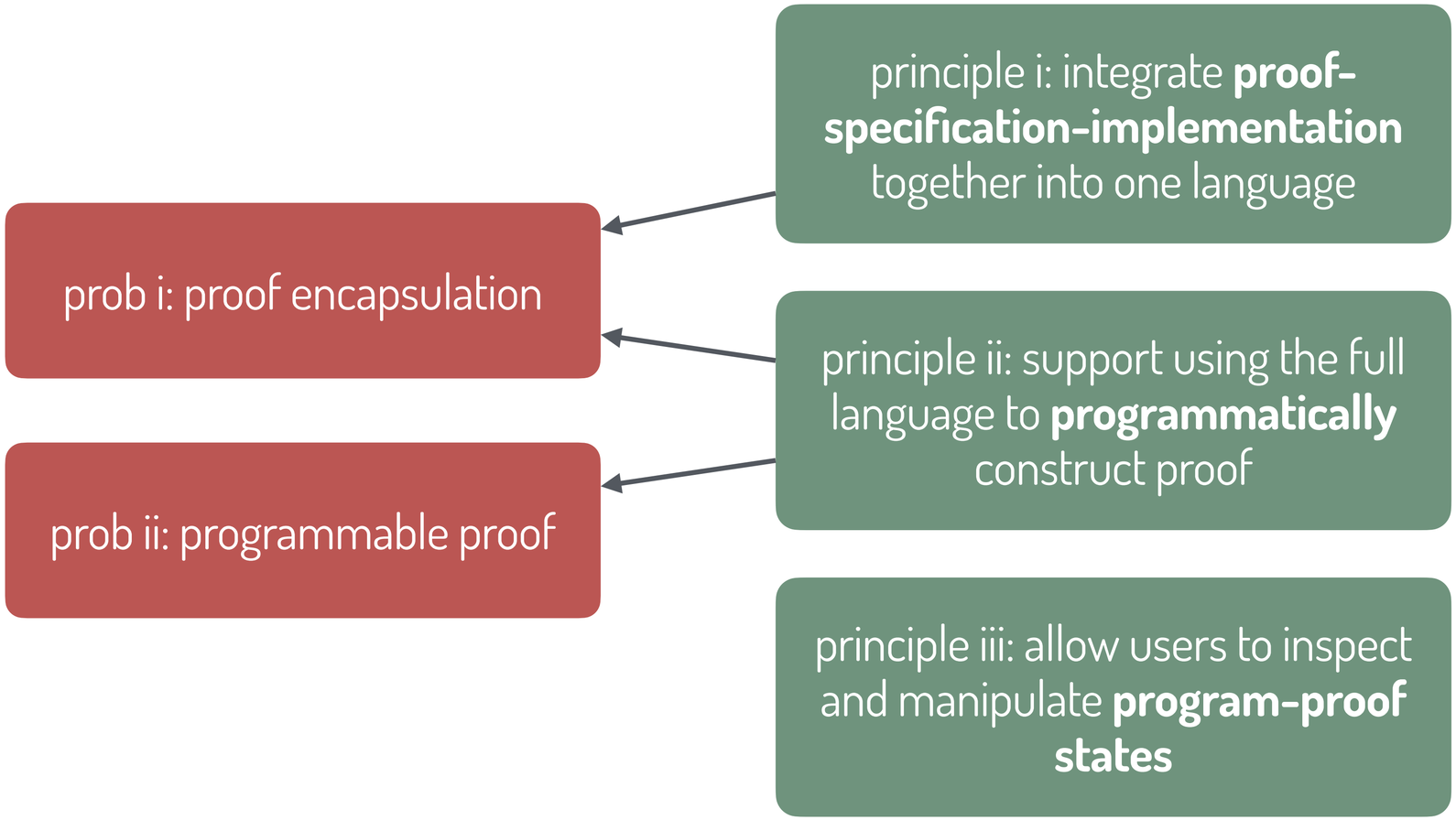

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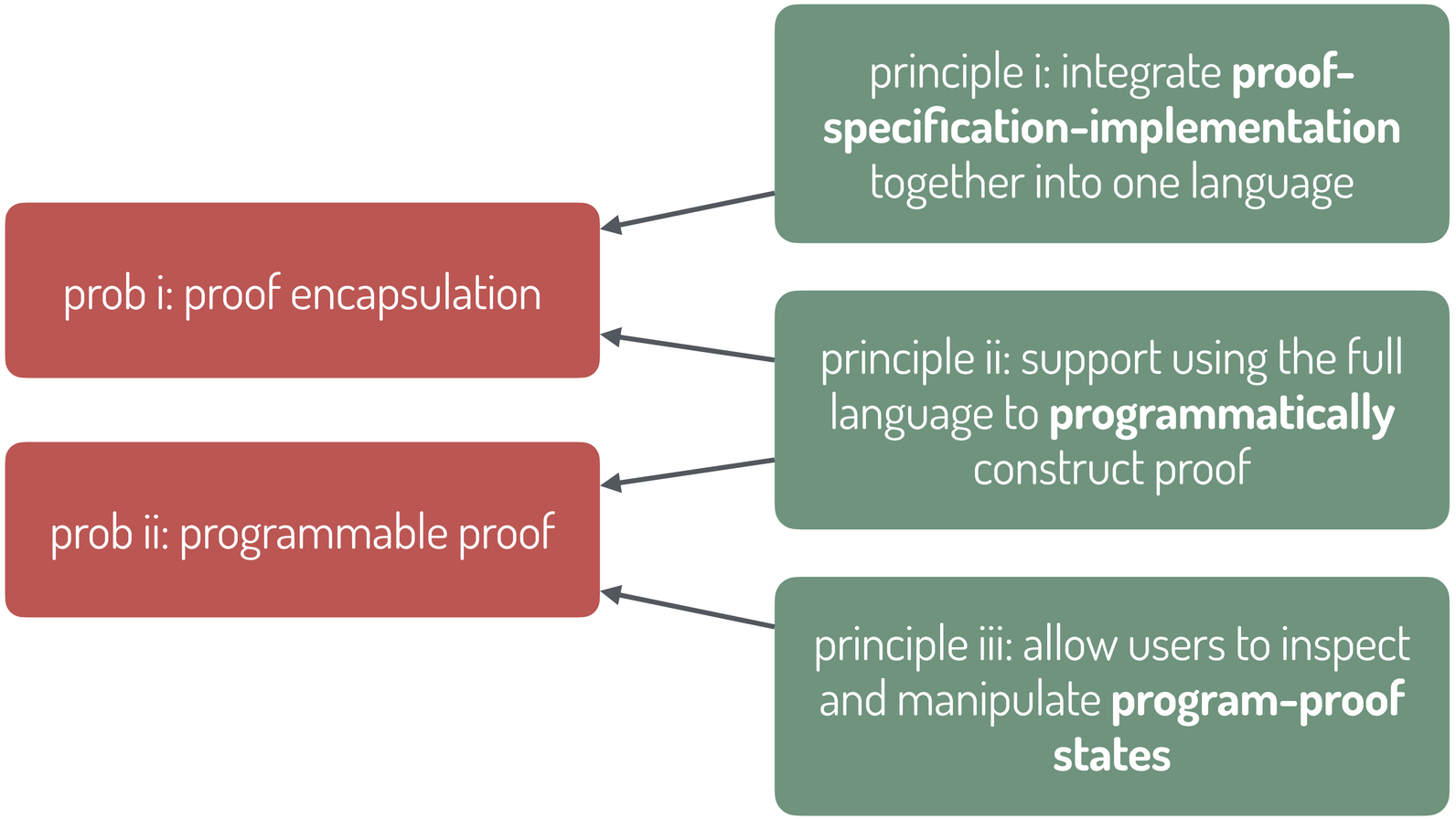

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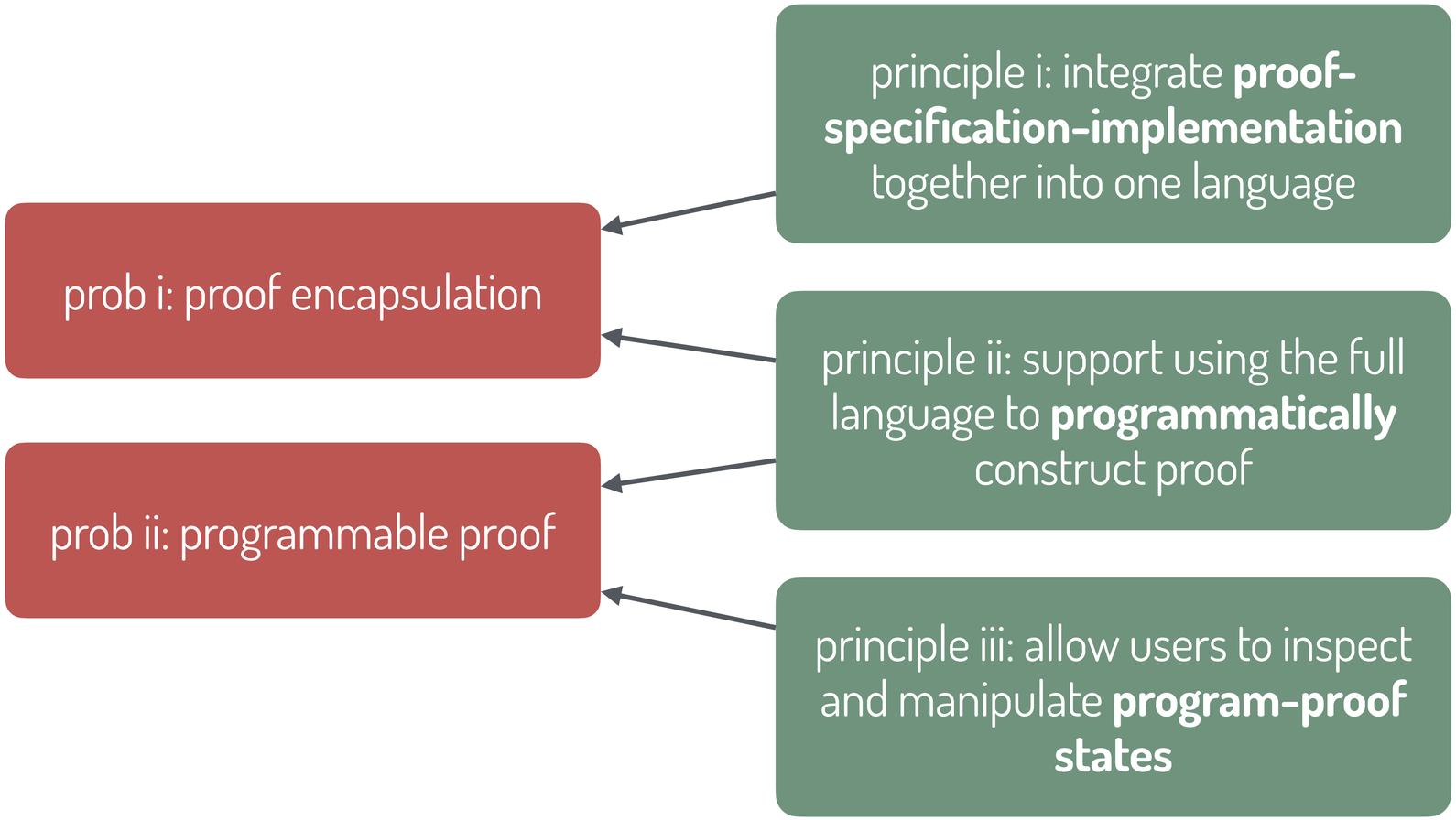

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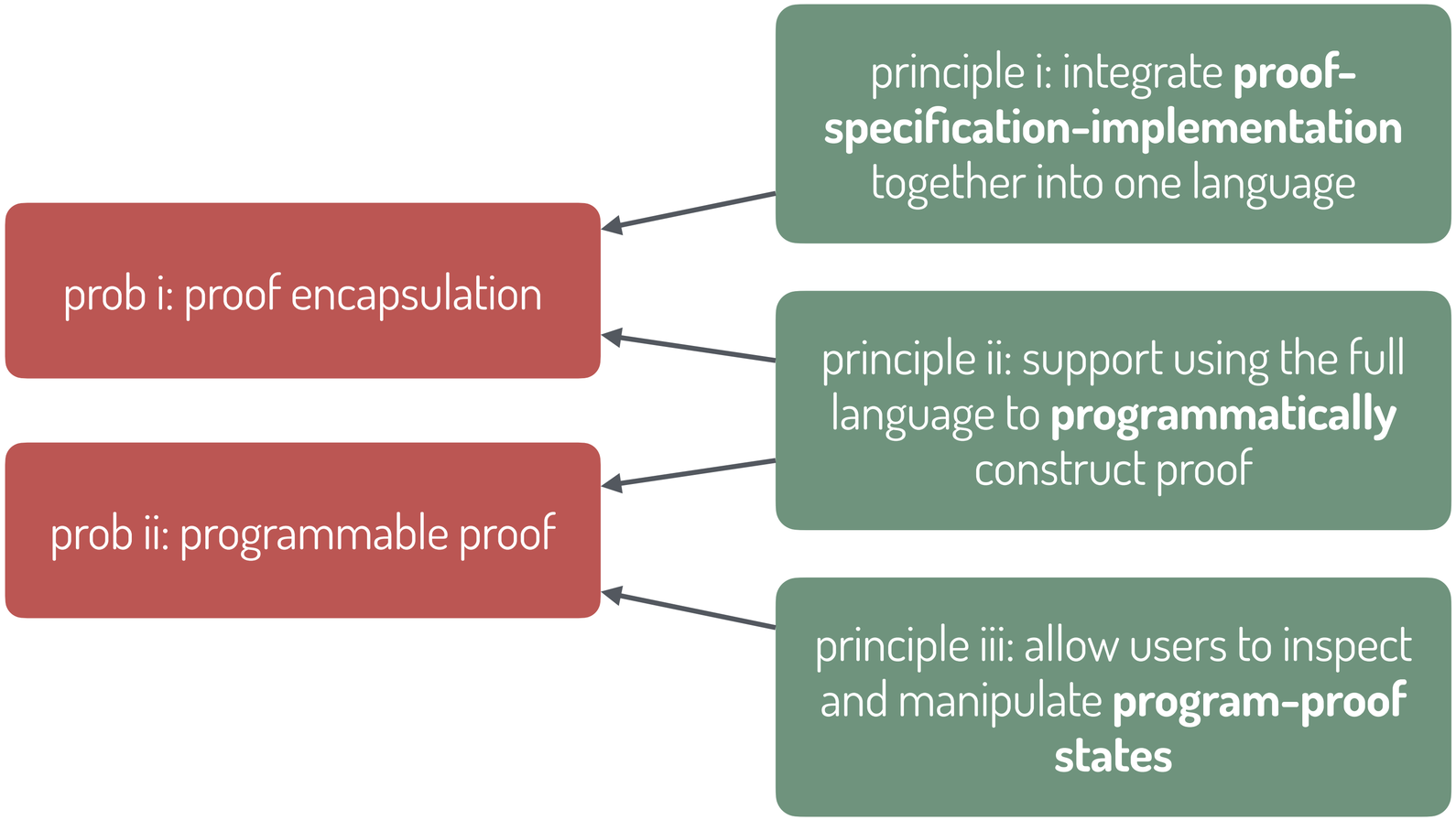

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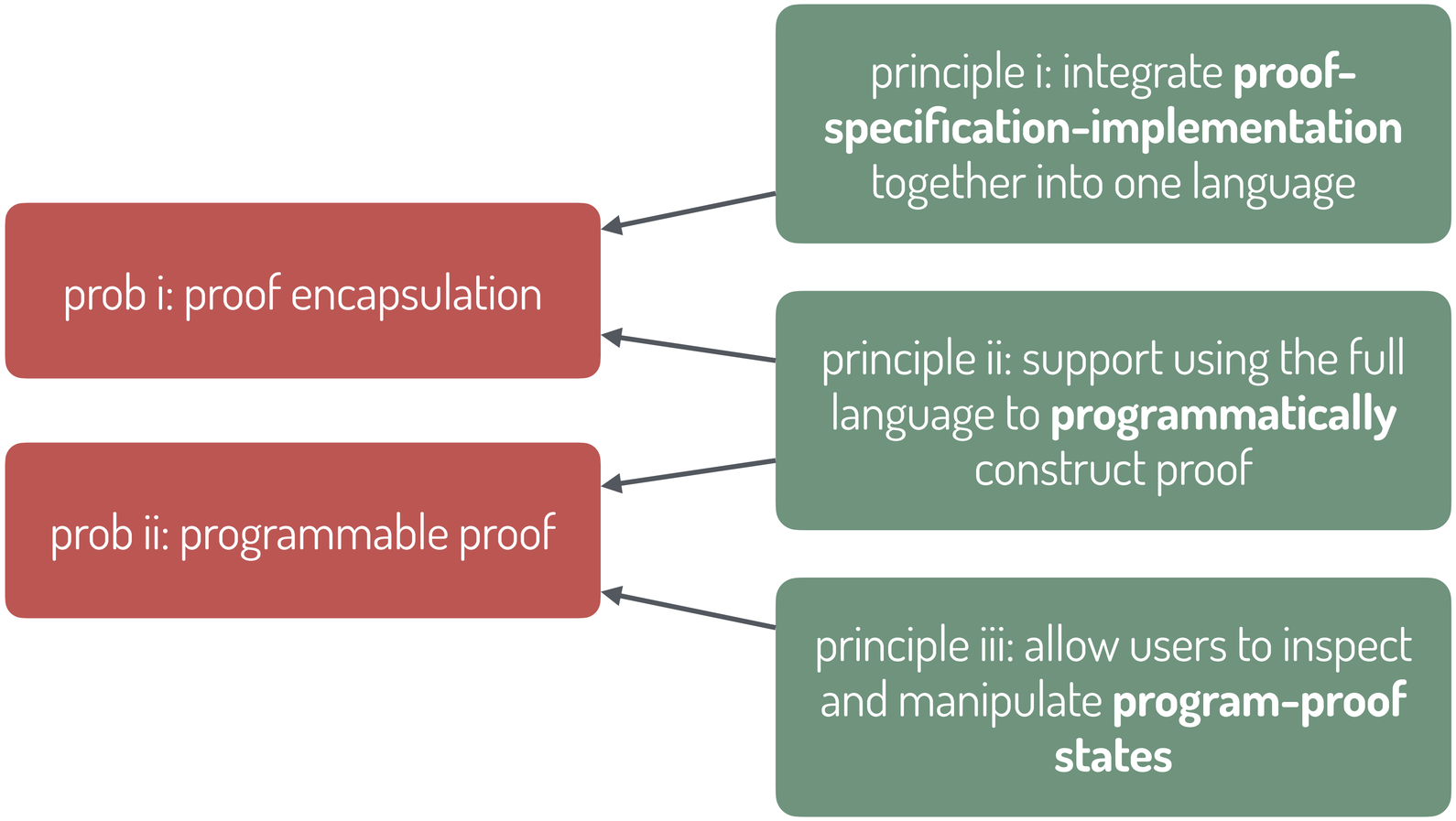

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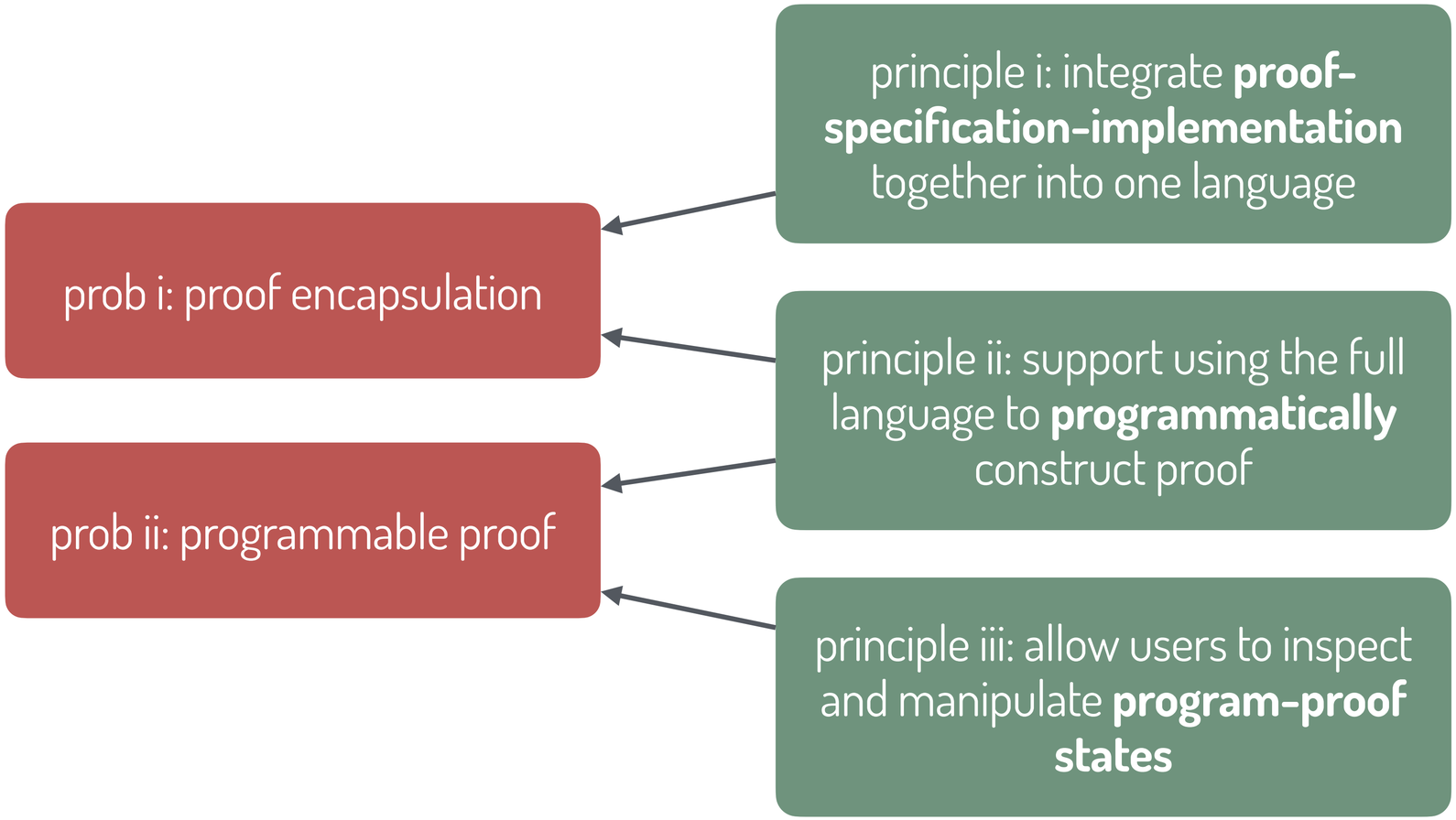

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  - you own language-Star?

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excerpts from the verified `attach_page` function in CN

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  - ongoing work: program-proof states reified as **local capabilities**

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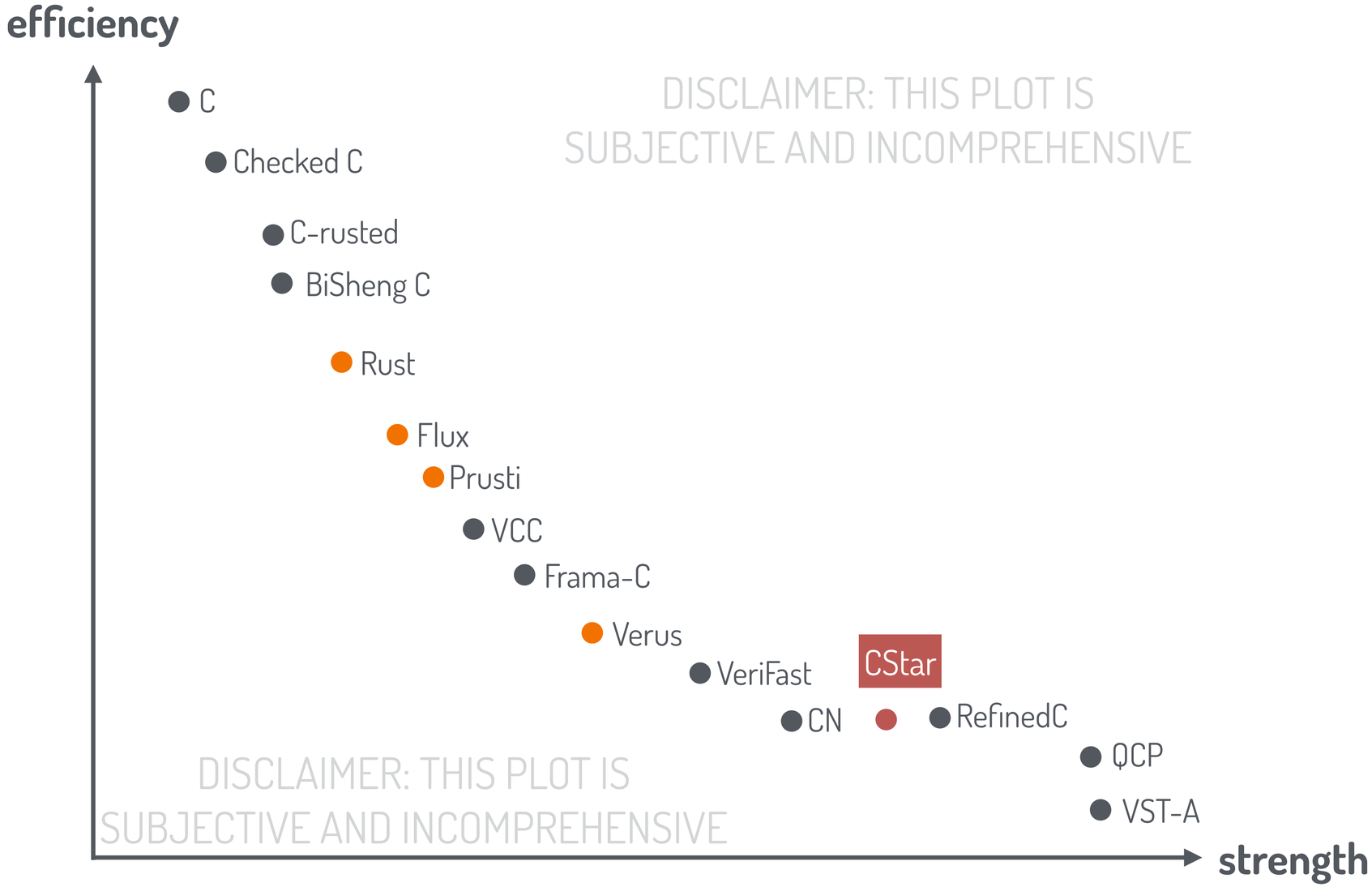
efficiency
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C
Checked C
C-rusted
BiSheng C
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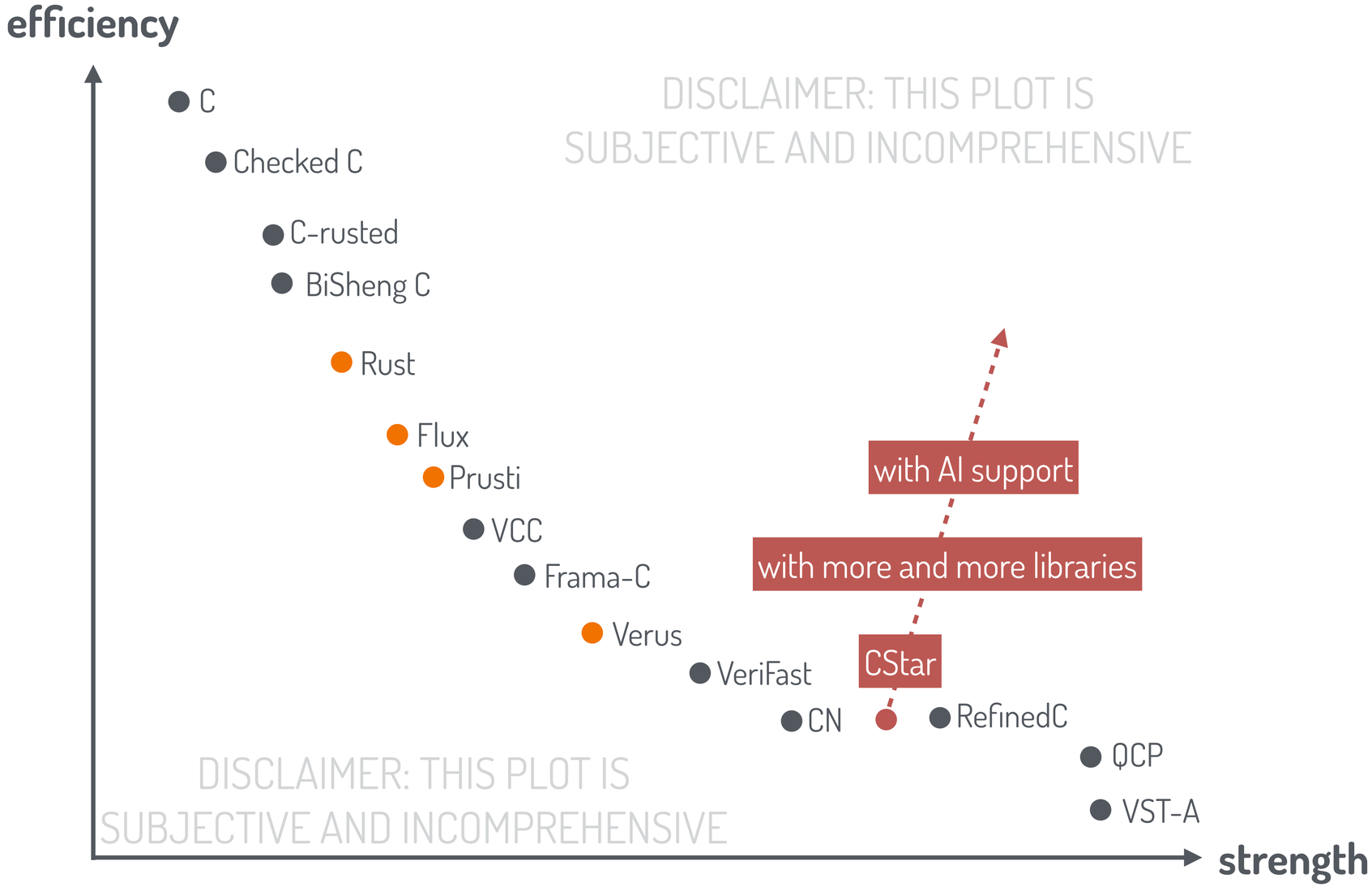
strength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VCC
Frama-C
Verus
VeriFast
CN
CStar
RefinedC
QCP
VST-A
with AI support
with more and more libraries
DISCLAIMER: THIS PLOT IS
SUBJECTIVE AND INCOMPREHENSIVE
strength