A Formal C Memory Model Supporting Integer-Pointer Casts

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Motivation

- **Integer-pointer cast is an important feature of C.**
  + used in Linux kernel, Java HotSpot VM
- **Pointers being integers invalidates optimizations.**
  + e.g. constant propagation
- **Want to support integer-pointer casts & optimizations**

Integer-Pointer Casts:
Importance in Practice

- **Example 1: Pointers as hash keys**

```
void hash_put(void* key, Data value);
Data hash_get(void* key);
```

- **Example 2: Pointer compression in Java HotSpot VM**

```
int32_t compress(void*);   // 64bit -> 32bit
void* decompress(int32_t); // 32bit -> 64bit
```

Identifying Pointers with Integers: Invalidates Constant Propagation

- **Anyone can access any address.**

```
extern void g();




char f() {
 char a = '0';
 g();
 return a; // -> return '0'
}
```

Identifying Pointers with Integers: Invalidates Constant Propagation

- **Anyone can access any address.**

```
void g() {
 char b = '2';
 char* p = &b + 0x20;
 *p = '1';
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char f() {
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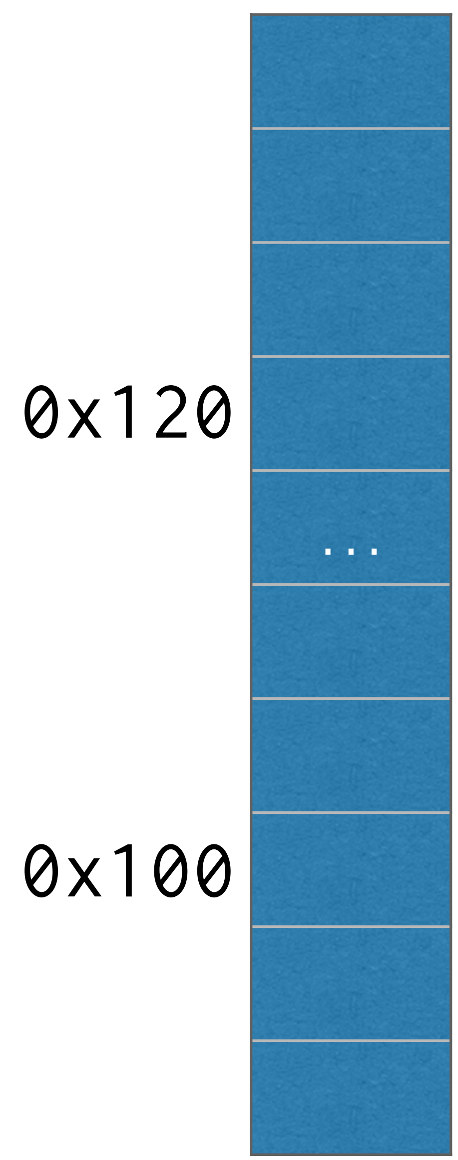
```



expr | value

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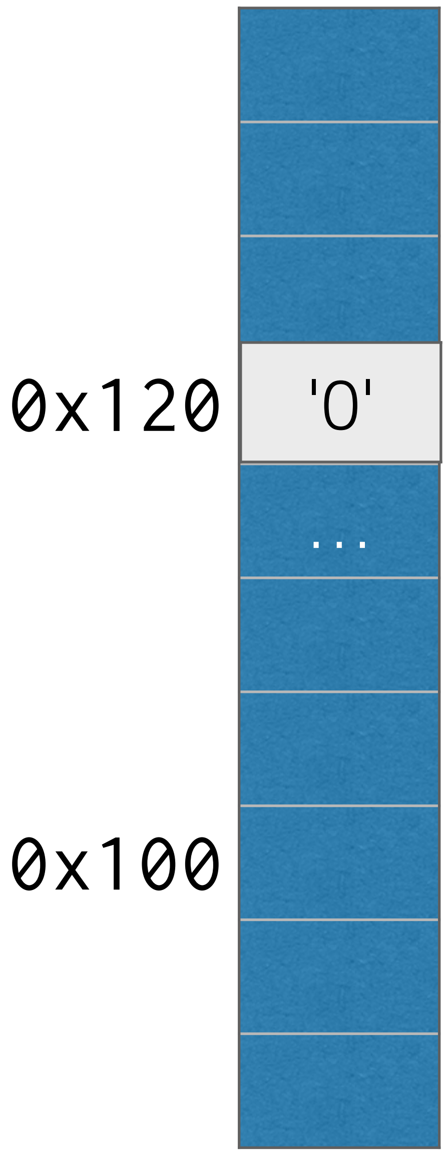

expr	value
&a	0x120

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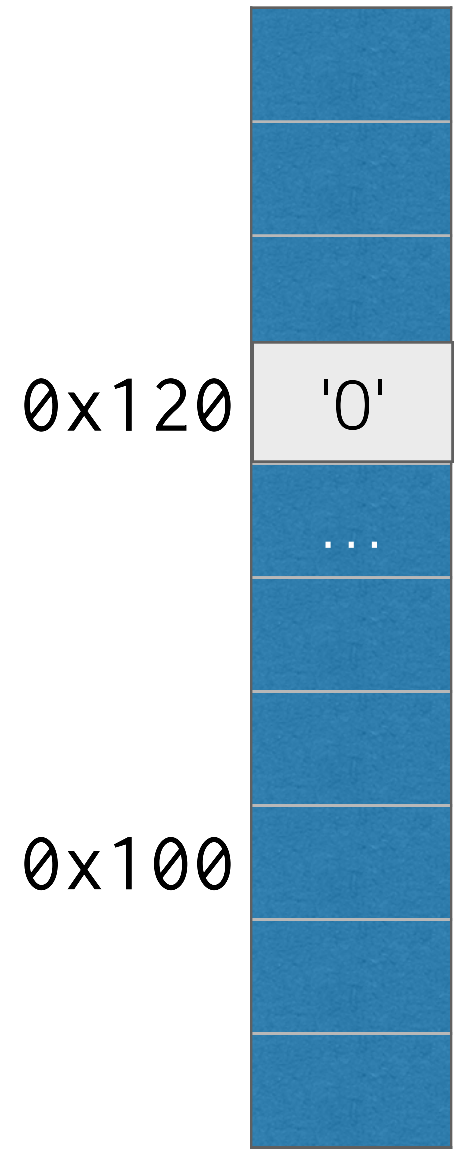

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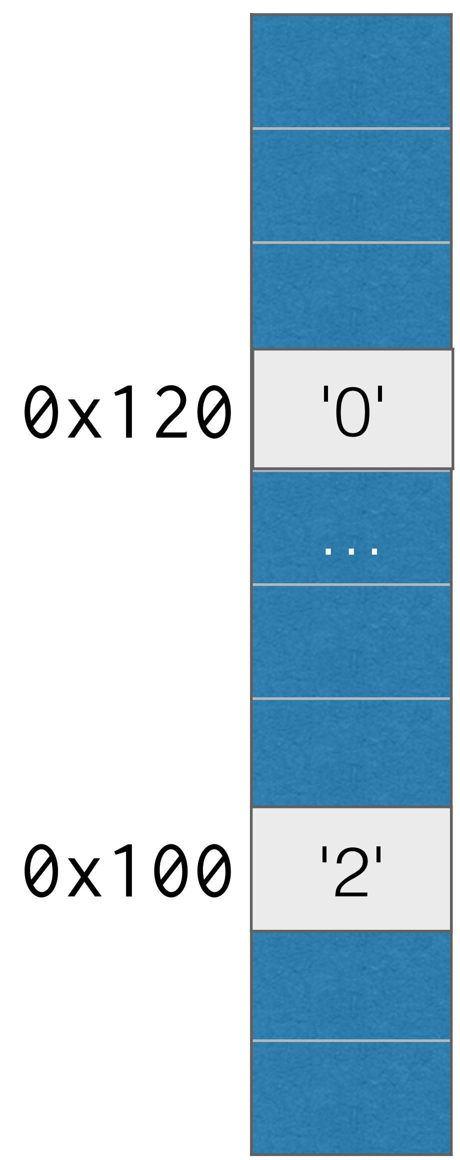

expr	value
&a	0x120
&b	0x100

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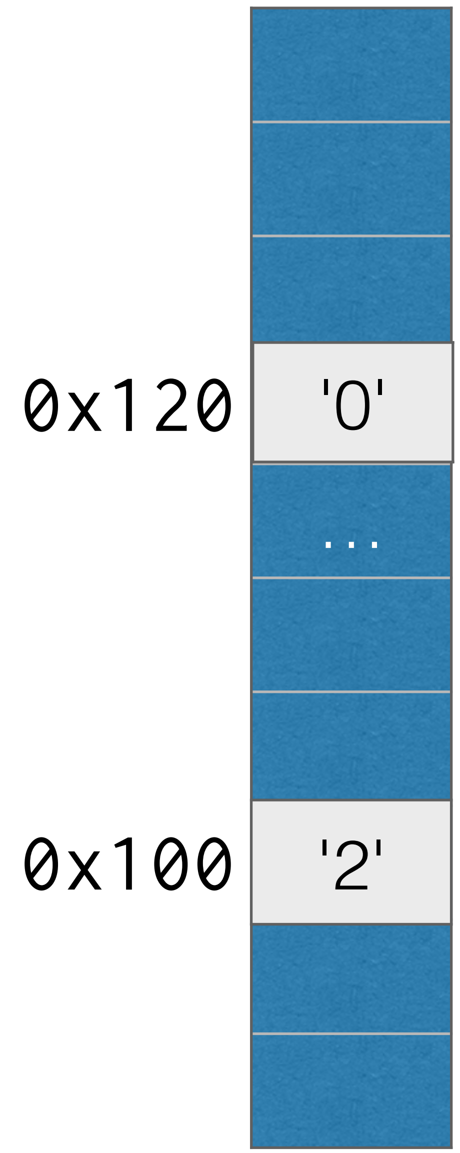

expr	value
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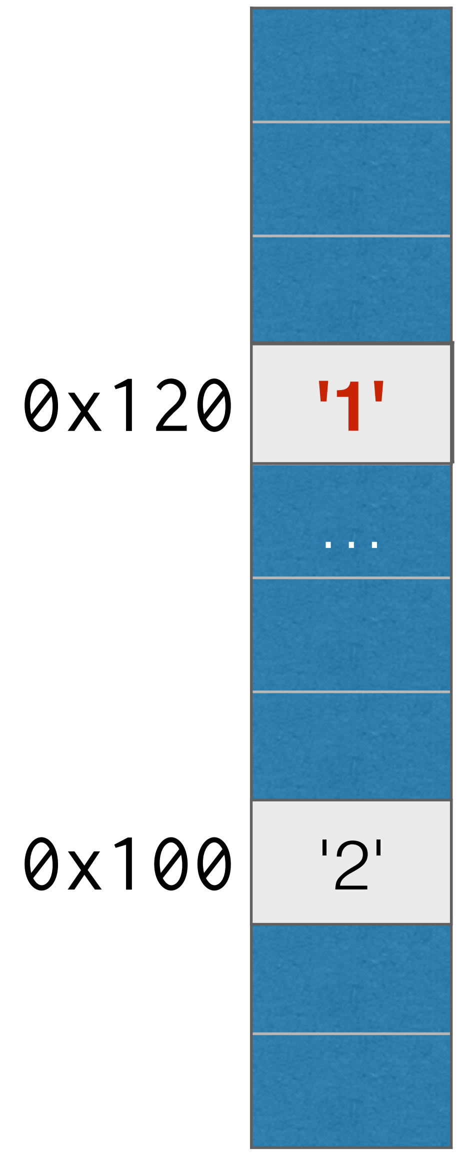

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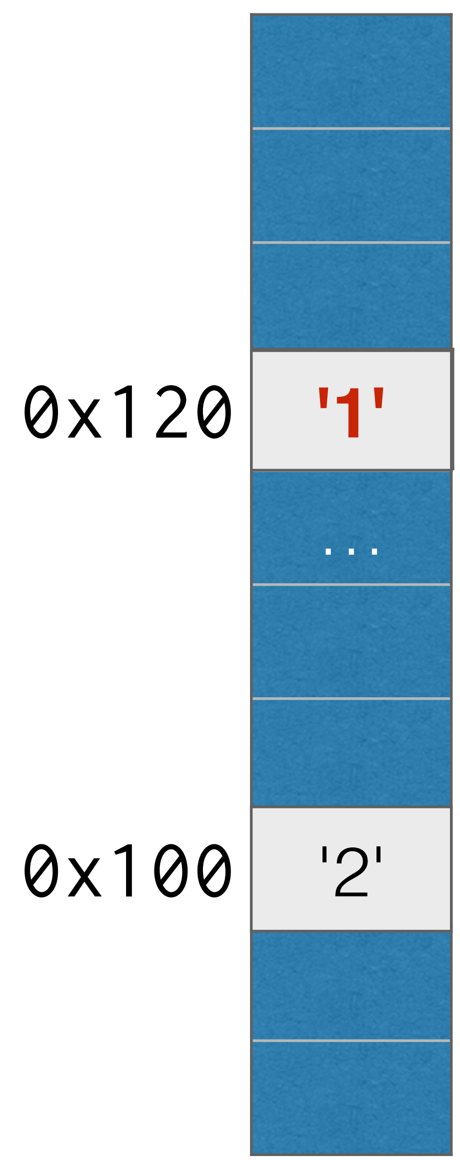

expr	value
&a	0x120
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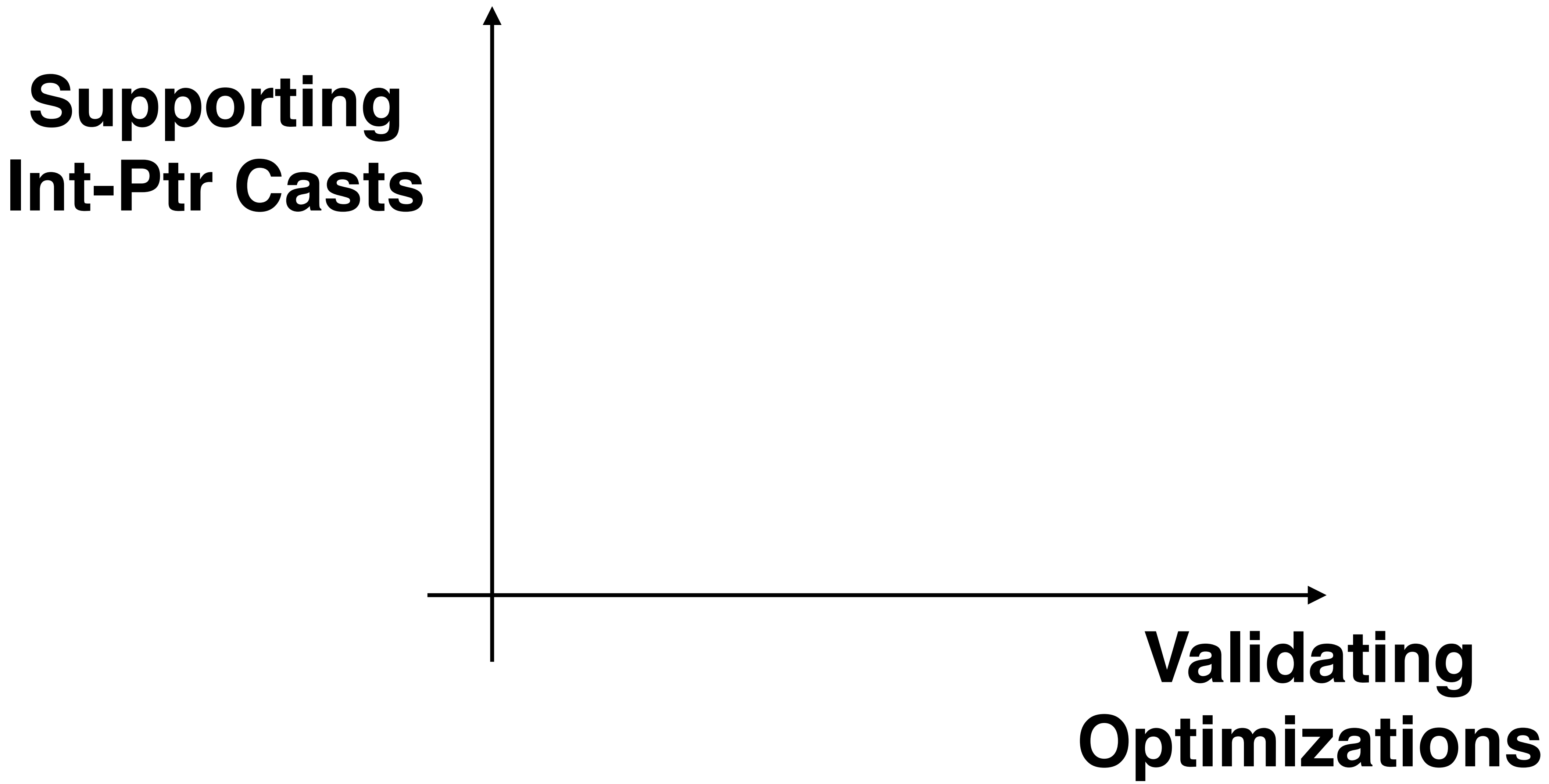
&b+0x20	0x120

Goal of Memory Model

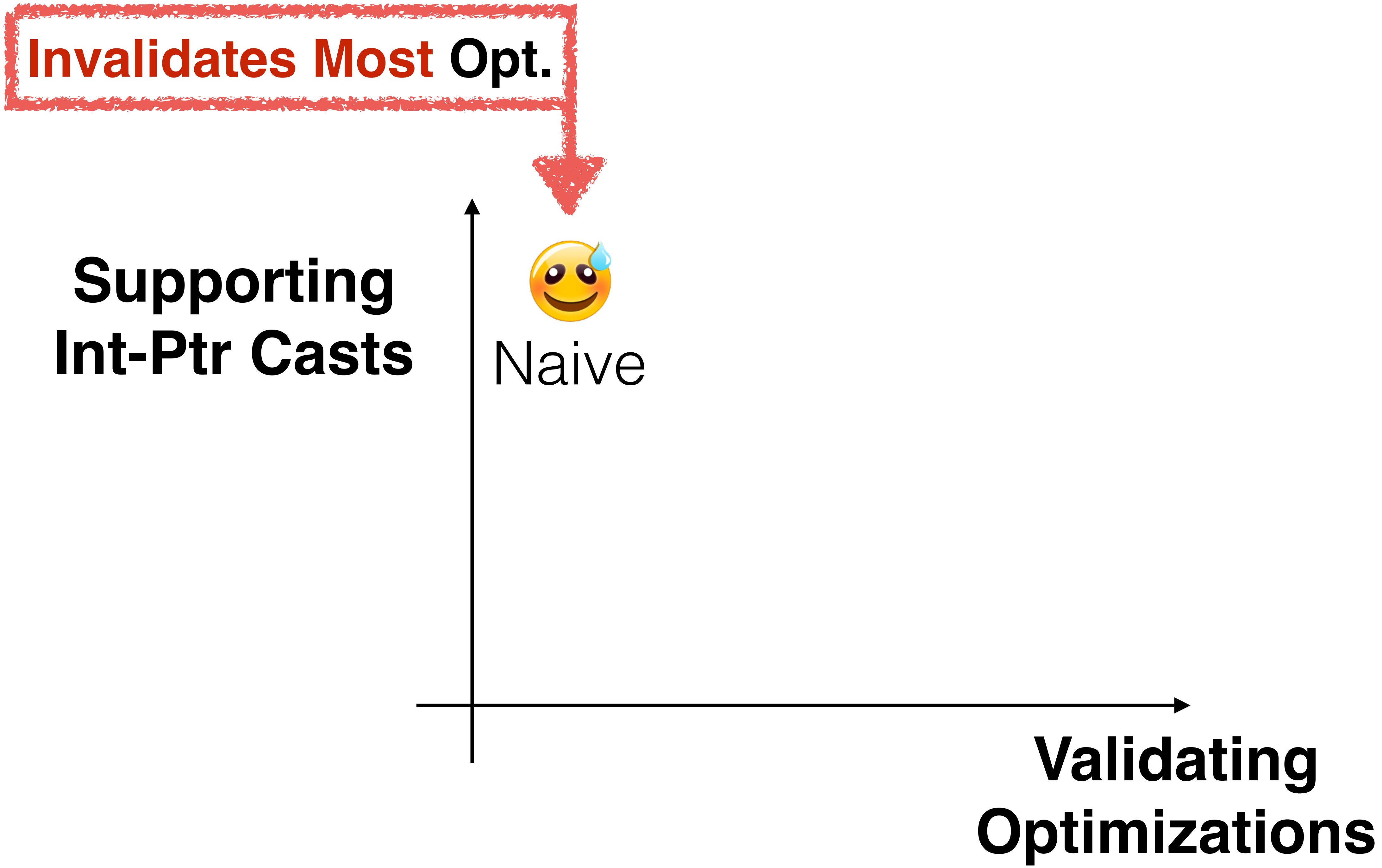
- To validate common optimizations
  by disallowing problematic memory accesses

- To allow integer-pointer casts

Outline



Outline


Invalidates Most Opt.
Supporting Int-Ptr Casts
Naive
Validating Optimizations

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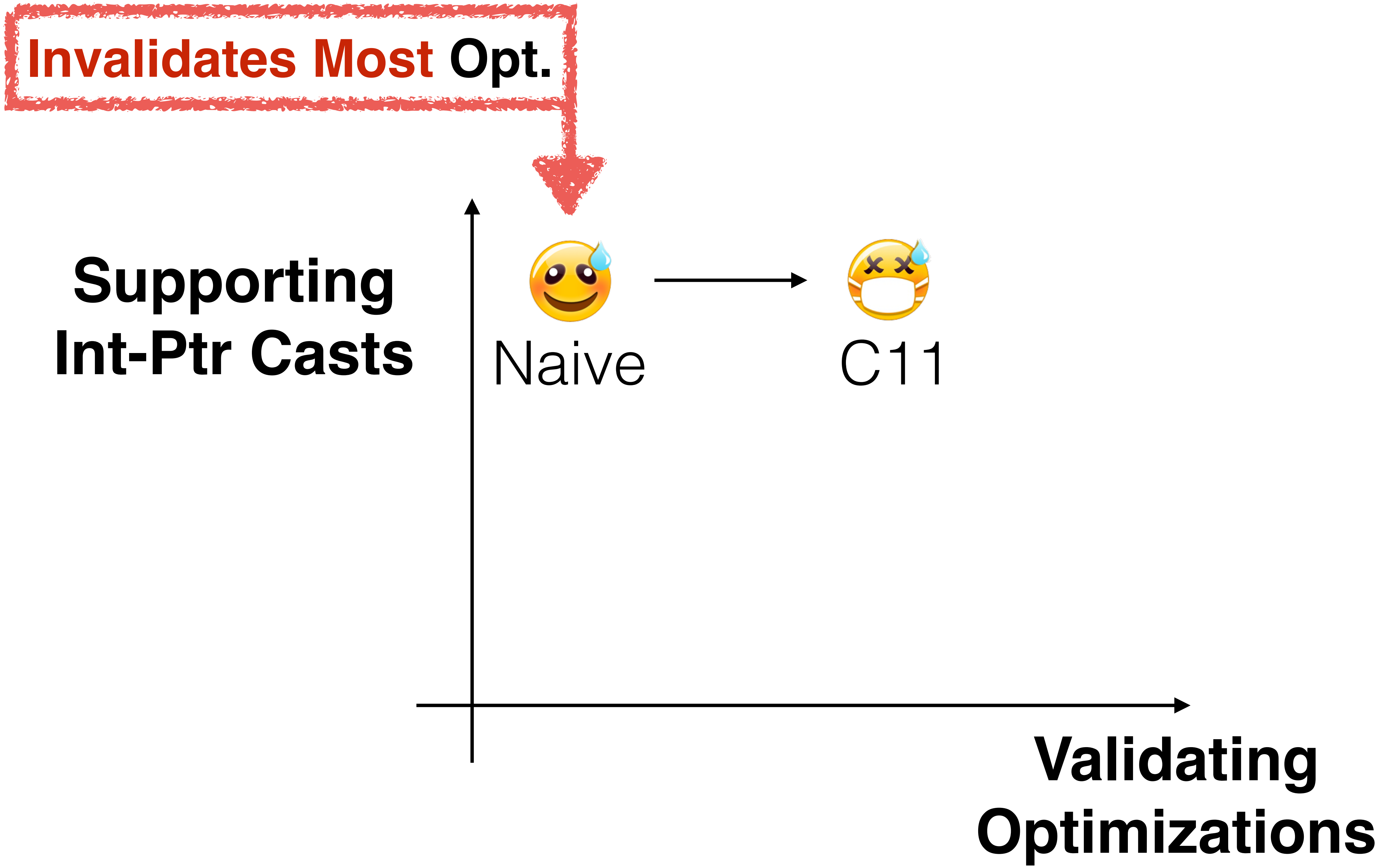

Invalidates Most Opt.
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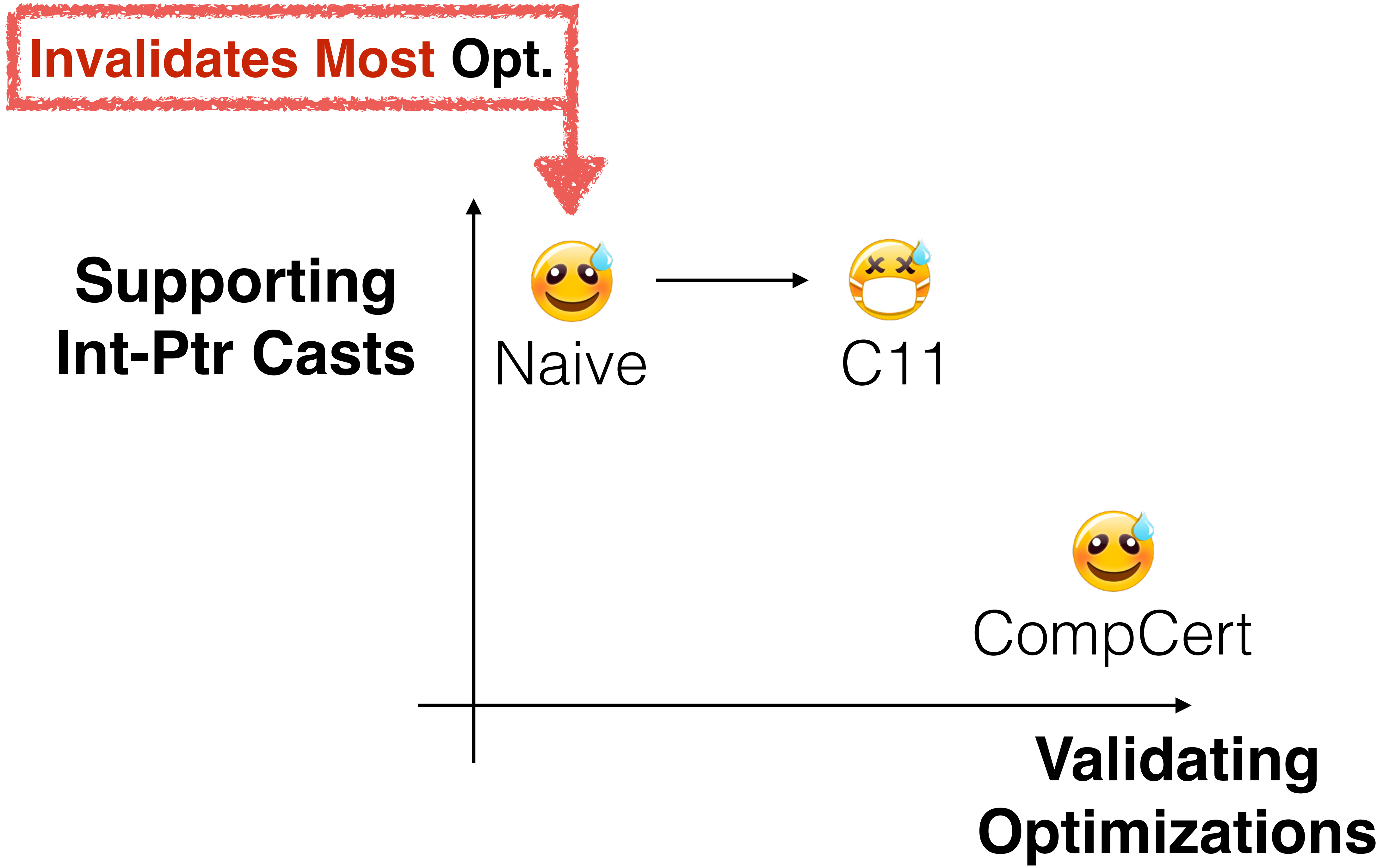
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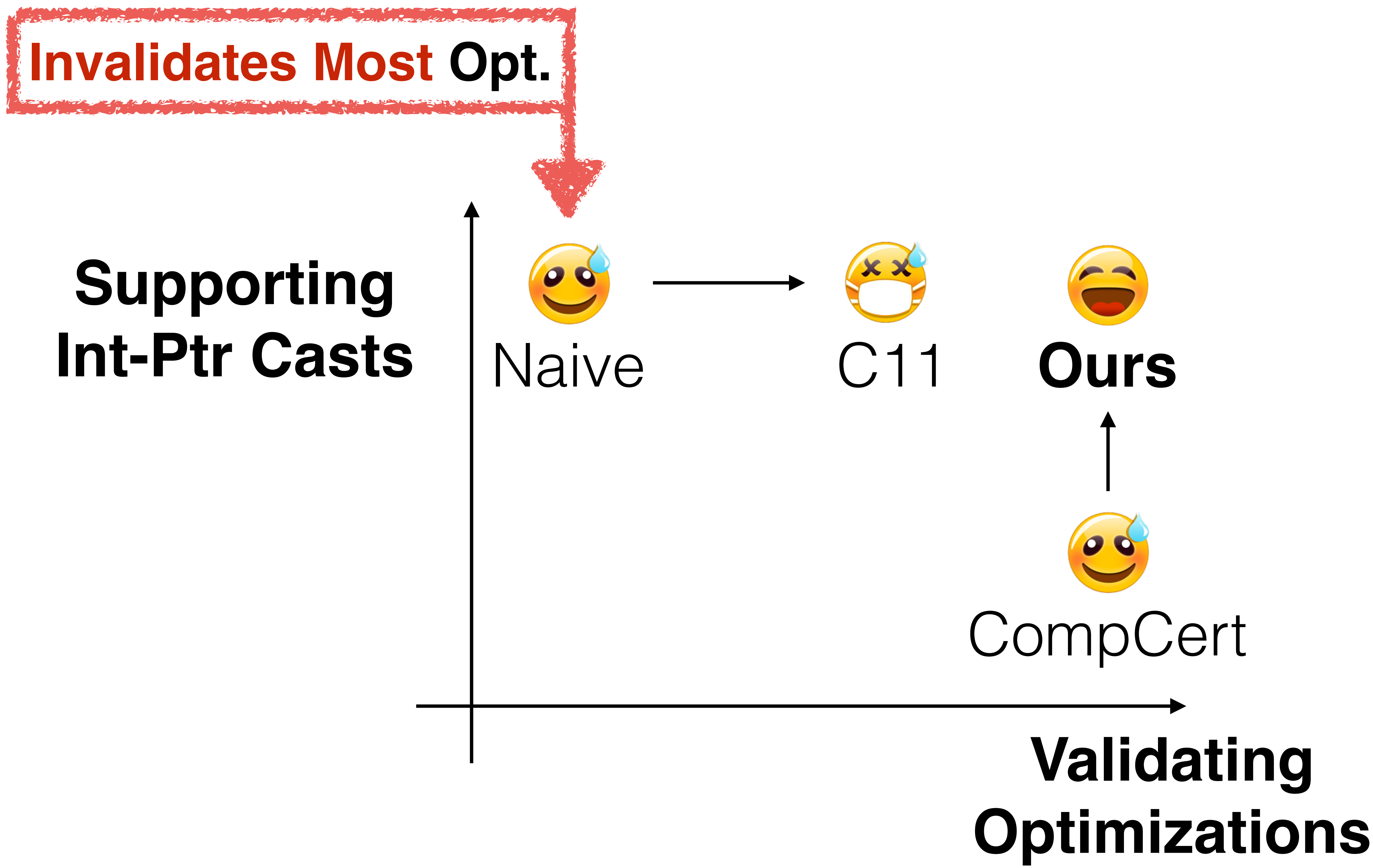
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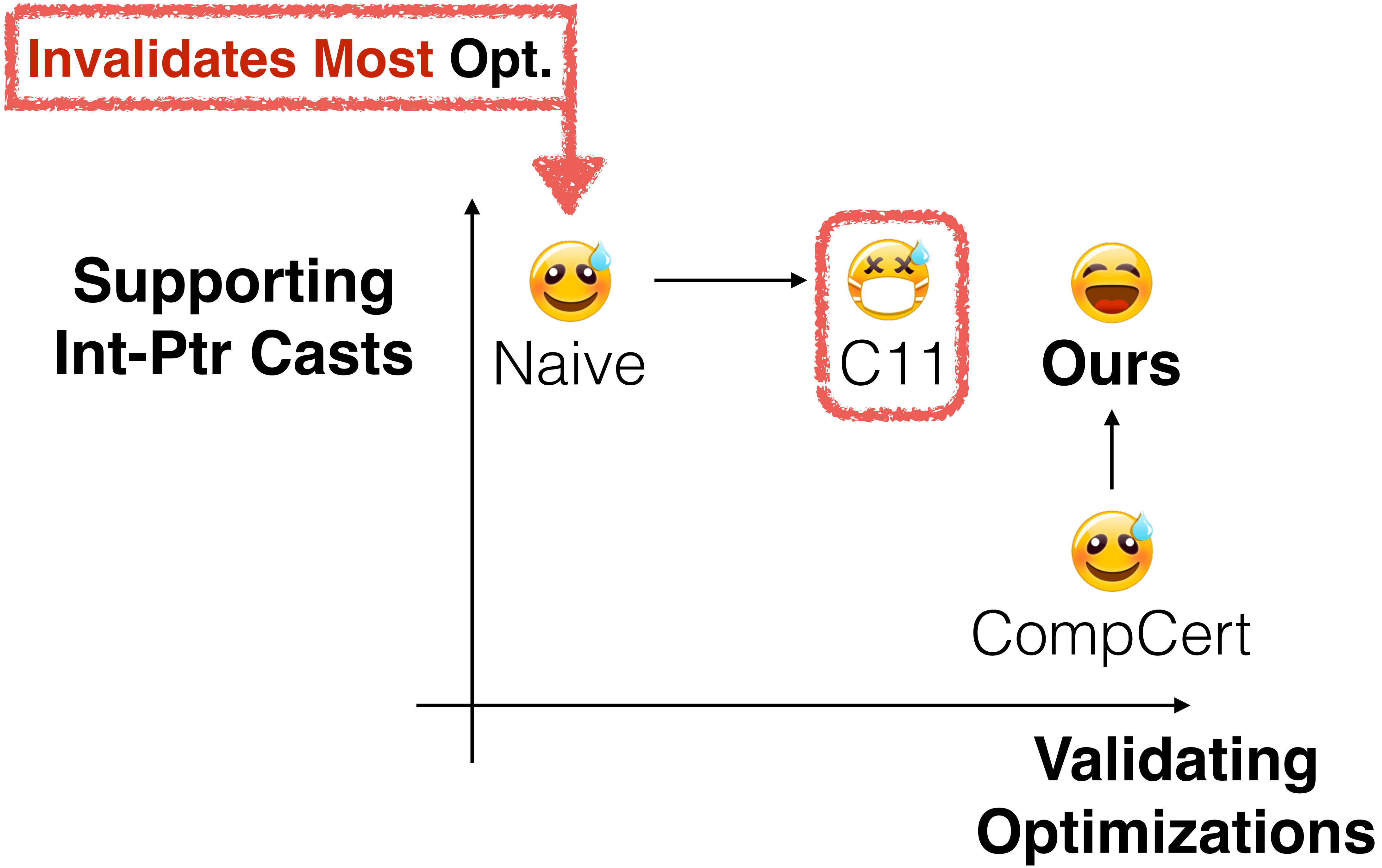

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C11 Model:
High-Level Idea

- **Integers & pointers are tagged with permission.**

Integers		**Pointers**
`0x120`	⟷	`0x120`
`0x100`	⟷	`0x100`

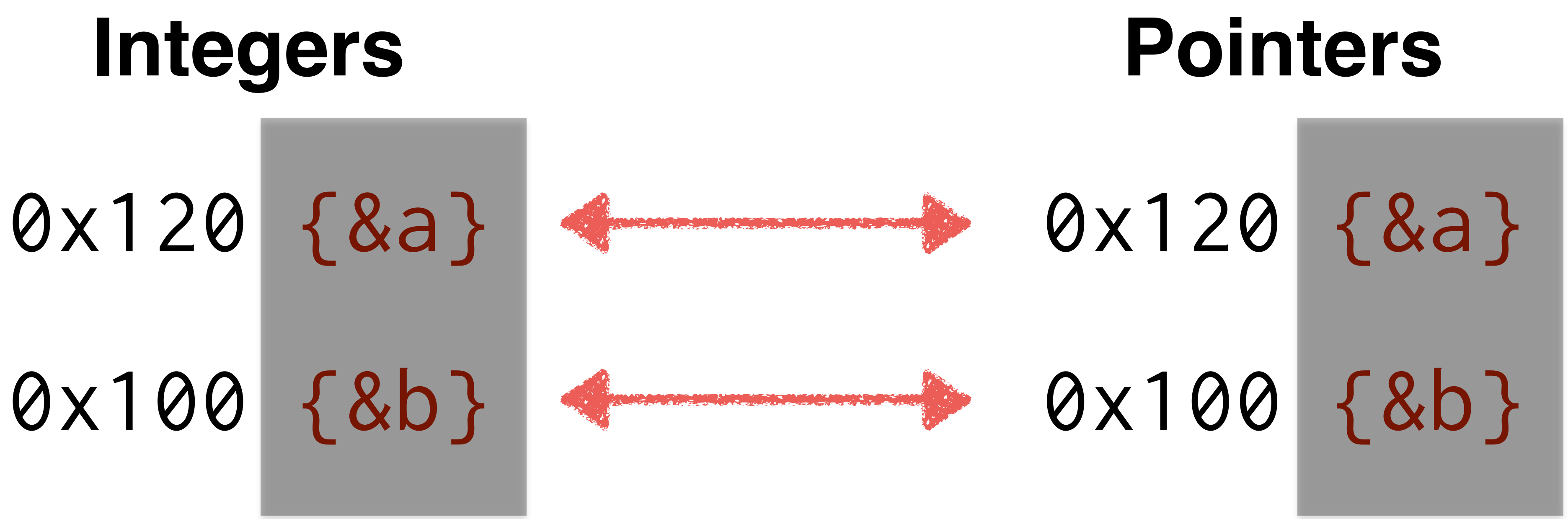
C11 Model:
High-Level Idea

- **Integers & pointers are tagged with permission.**

Integers		**Pointers**
`0x120 {&a}`	⟷	`0x120 {&a}`
`0x100 {&b}`	⟷	`0x100 {&b}`

C11 Model:
High-Level Idea

- **Integers & pointers are tagged with permission.**



C11 Model:
Protection by Permission

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void g() {
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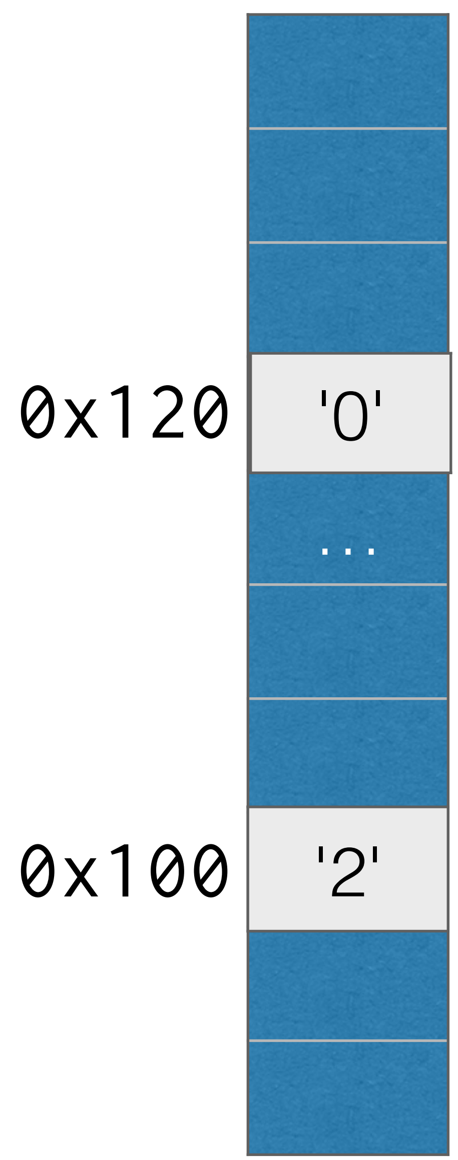

expr	value {perm.}
&a	0x120
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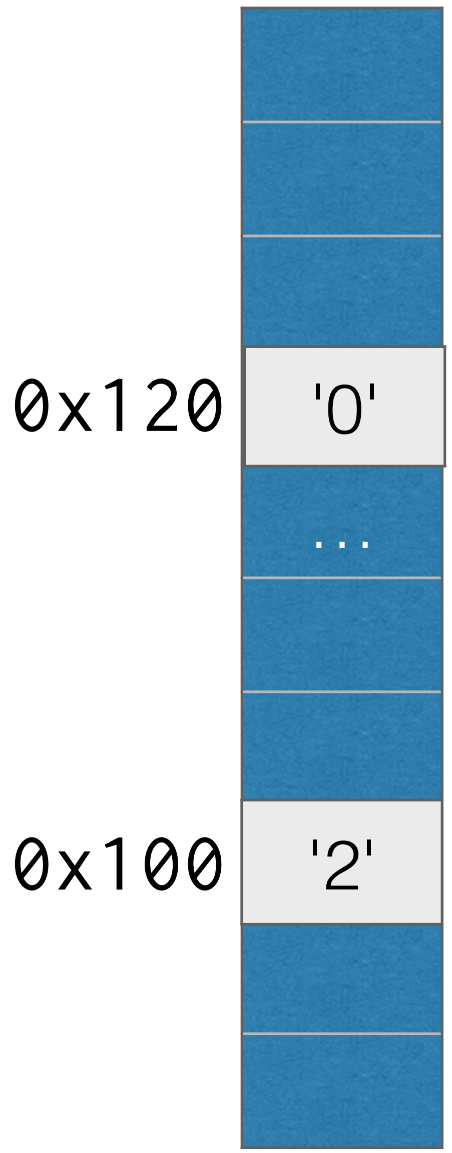

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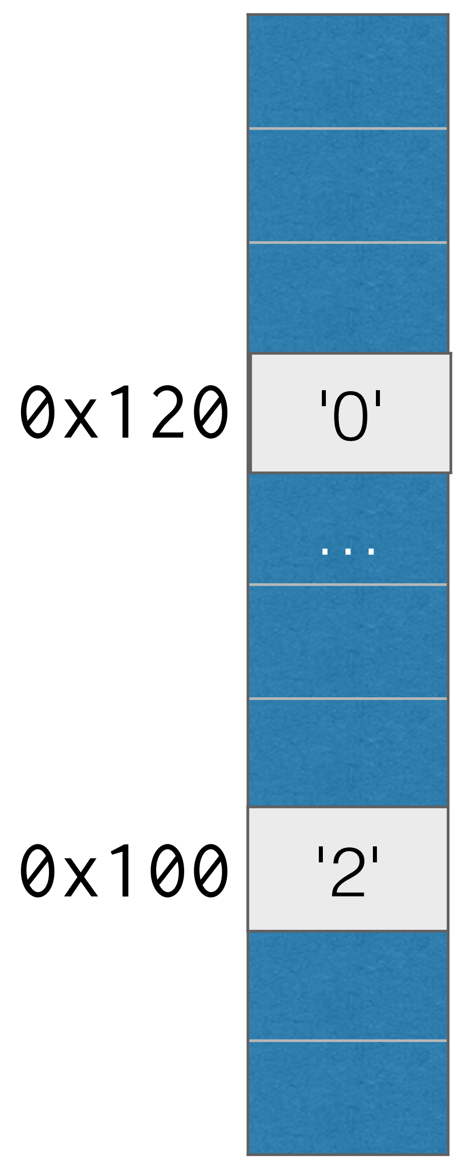

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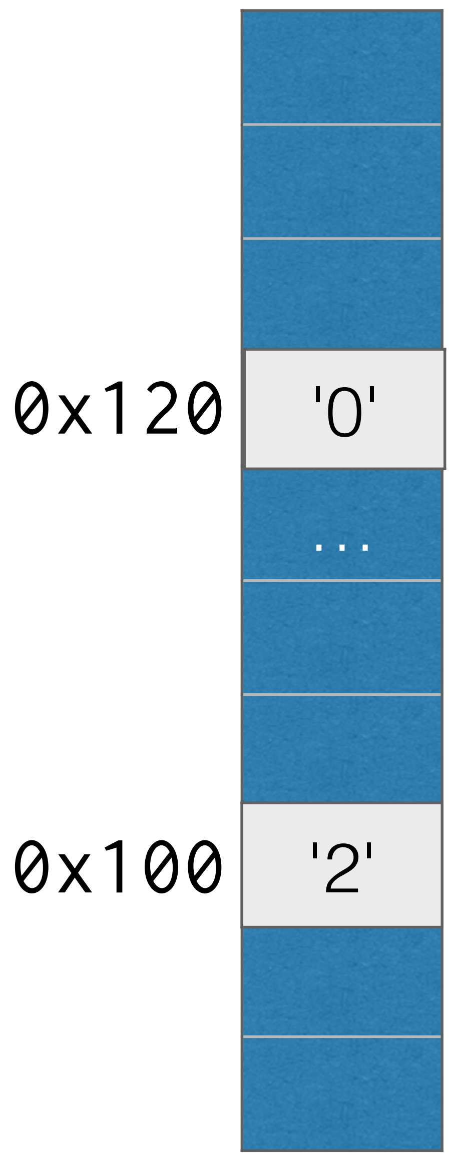

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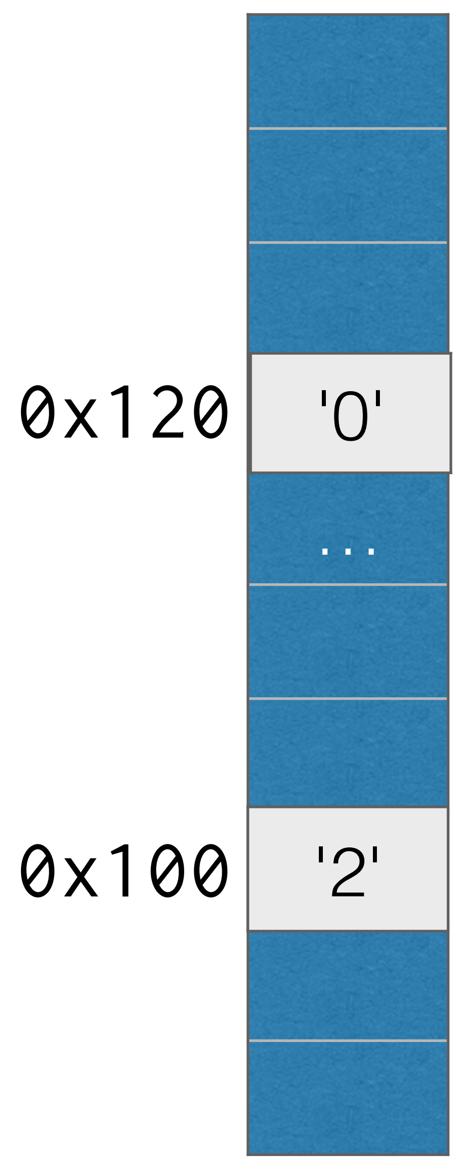

expr	value {perm.}
&a	0x120 {&a}
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&b+0x20	0x120 {&b}

Cannot Access a

C11 Model's Problems (1/2): Too Complex Semantics

- **Integers also need to carry permission.**
  Since integer-pointer casts should preserve permission.

- **Operations need to properly calculate permission.**

```
int y = x - x; // -> int y = 0;
```

expr	value
`x`	`0x100 {&a}`
`x - x`	`0x000 {? } -> 0x000 {}`

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expr	value
`x`	`0x100 {&a}`
`x - x`	`0x000 {&a} -> 0x000 {}` 😅

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```
int y = x - x; // -> int y = 0;
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expr	value
`x`	`0x100 {&a}`
`x - x`	`0x000 {  } -> 0x000 {}`
`2 * x`	`0x200 {? }`
`x XOR x`	`0x000 {? }`
…	…

C11 Model's Problems (2/2): Invalidates Some Optimizations

- **A useful code motion is not allowed.**

```
int a, b;
…
if (a != b) {
  a = b;
}
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```
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…
if (a != b) {
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```

expr	value
a	`0x100 {&x} -> 0x100 {}`
b	`0x100 {}`

C11 Model's Problems (2/2): Invalidates Some Optimizations

- **We found a real GCC bug.**

Integer type for pointers

```
void main() {
  int x = 0;
  uintptr_t xi = (uintptr_t) &x;
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", x); } // prints 1
```

https://gcc.gnu.org/bugzilla/show_bug.cgi?id=65752

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Integer type for pointers

DEAD CODE

```
void main() {
  int x = 0;
  uintptr_t xi = (uintptr_t) &x;
  uintptr_t i;
  for (i = 0; i < xi; ++i) {}
  if (xi != i) {
    printf("unreachable\n");
    xi = i;
  }
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", x); } // prints 0
```

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  }
  xi = i; // code motion
  int* p = (int*) xi;
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```

i | … {}

xi | … {}

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    printf("unreachable\n");
  }
  xi = i; // code motion
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", 0); } // constant propagation x -> 0
```

DEAD CODE

i | … {}

xi | … {}

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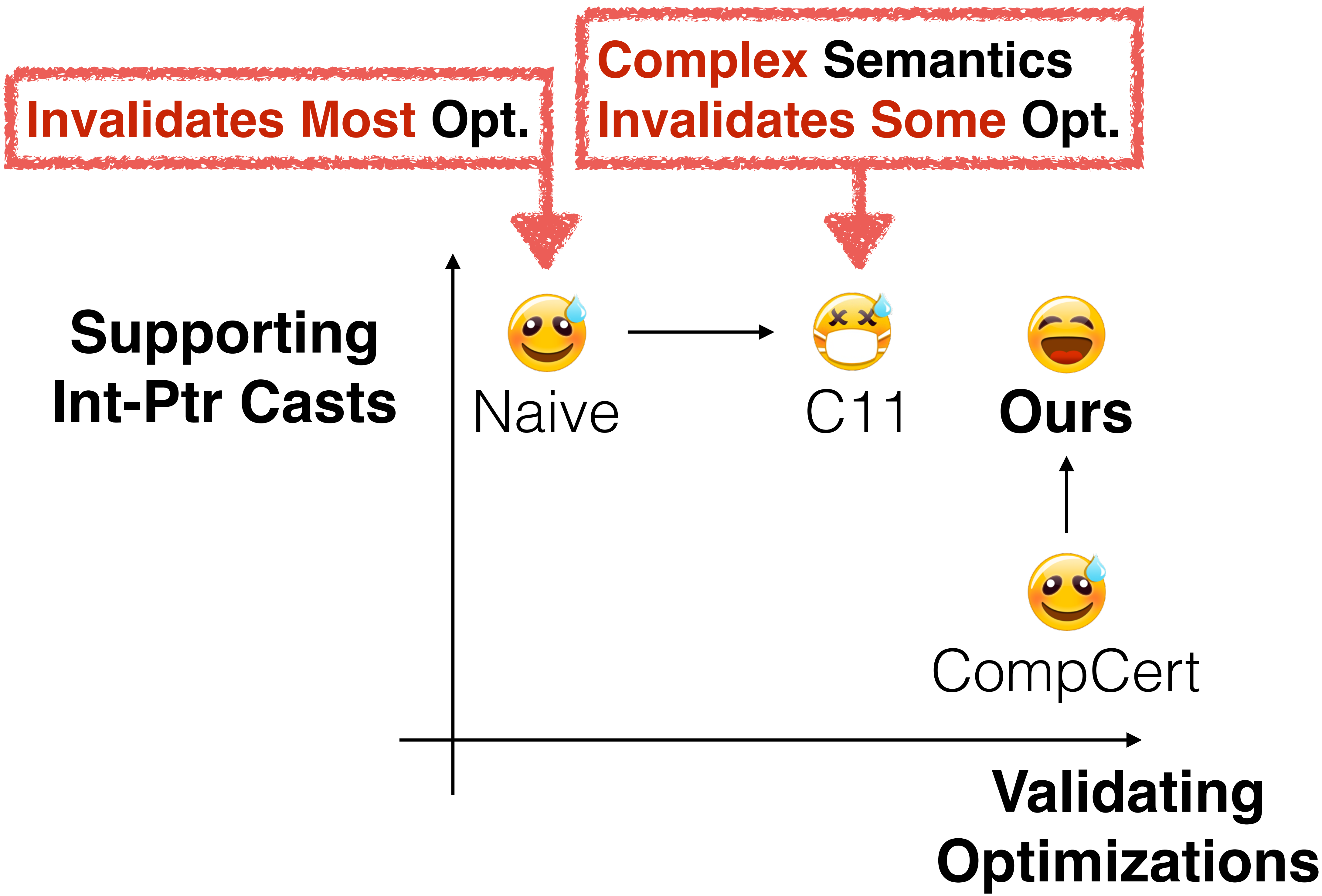
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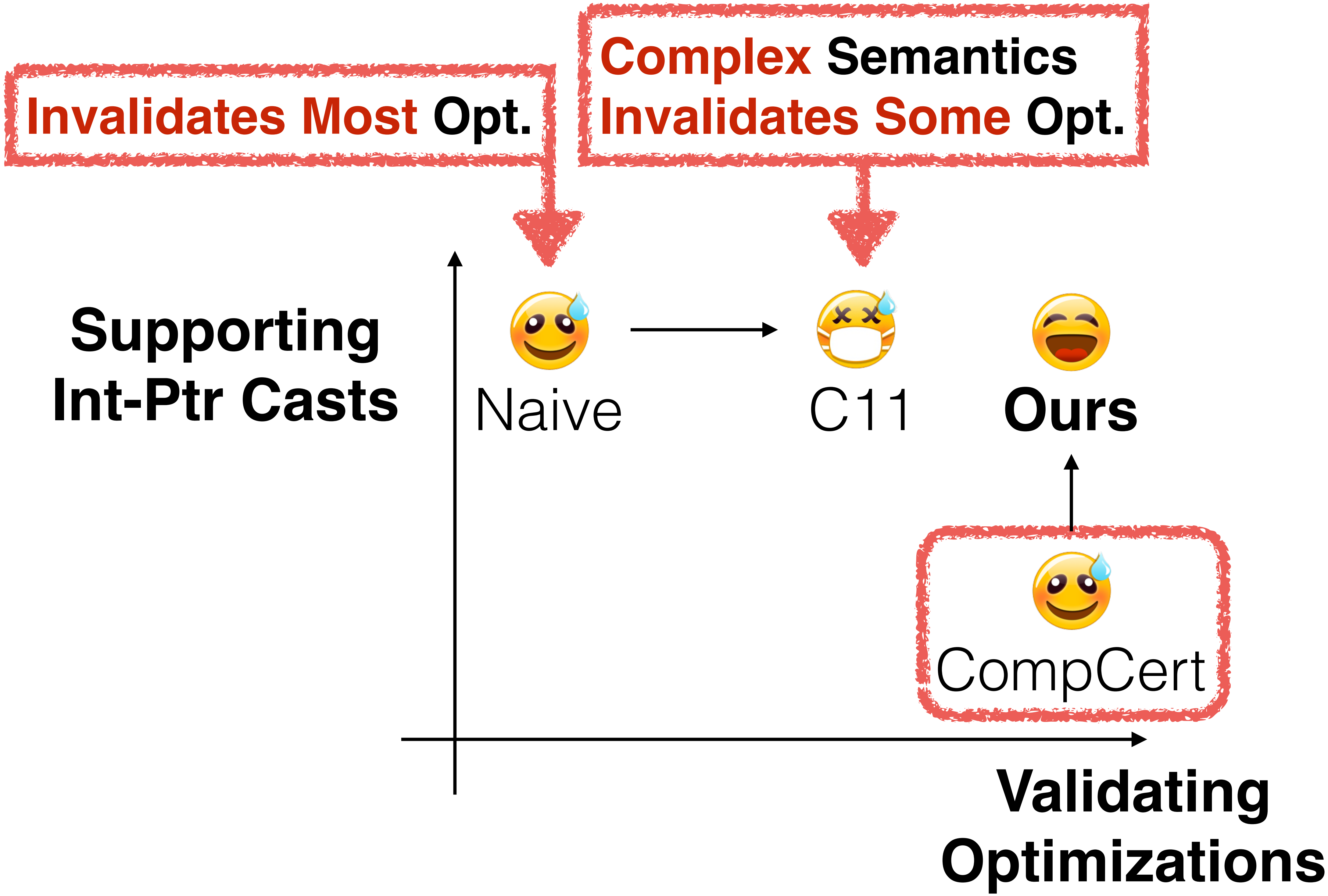
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CompCert Model:
High-Level Idea

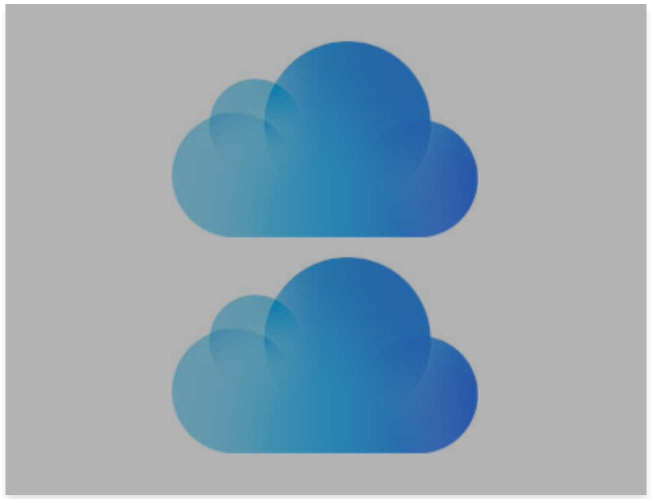
- **Pointers are different from integers.**

Integers

`0x120`

`0x100`

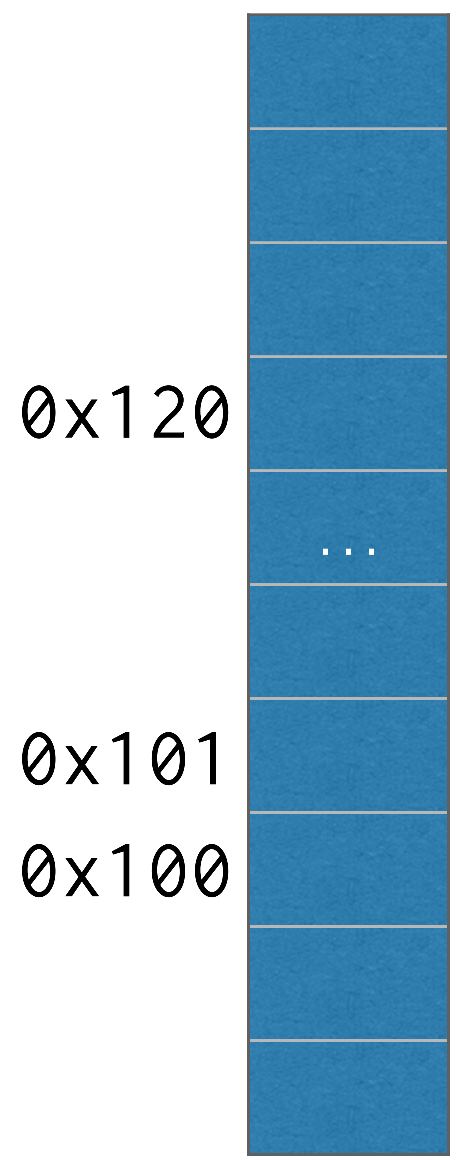
Pointers



CompCert Model:
Protection by Logical Blocks

```
void g() {
 char b[2]={'2','3'};
 char* p = b + 0x20;
 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```

Naive



CompCert

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char f() {
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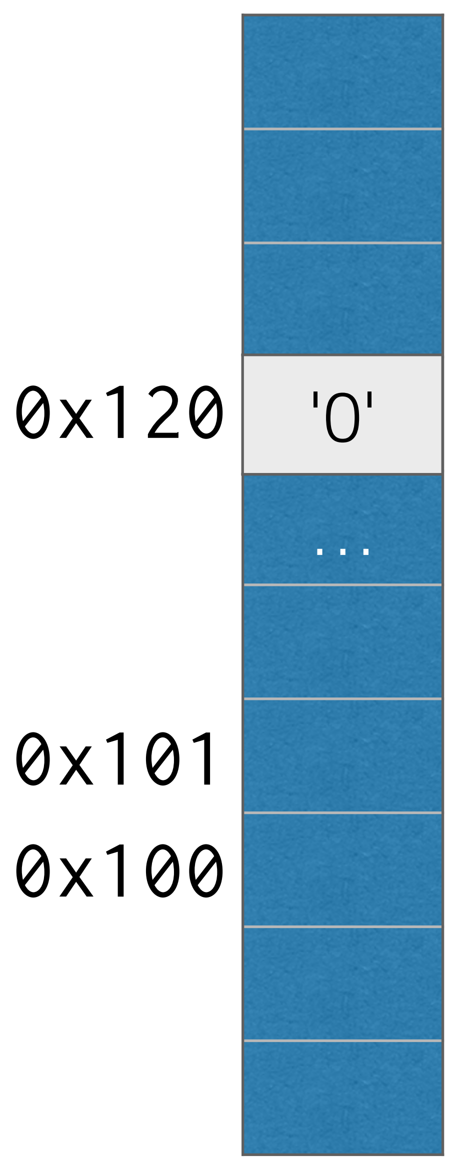
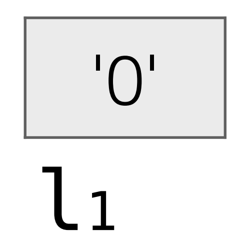
  g();
  return a; // -> '0'
}
```

&a | 0x120

Naive



CompCert



&a | $(l_1, 0)$

CompCert Model:
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```
void g() {
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 char* p = b + 0x20;
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}
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 g();
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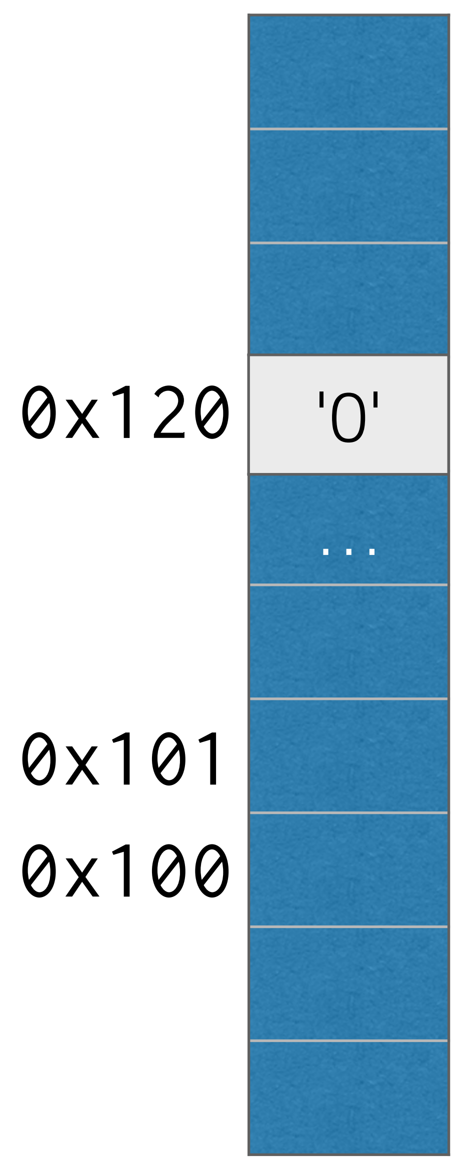
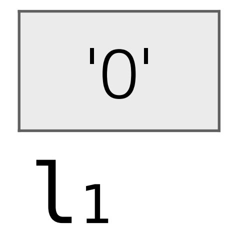
}
```

&a | 0x120

Naive



CompCert



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CompCert Model:
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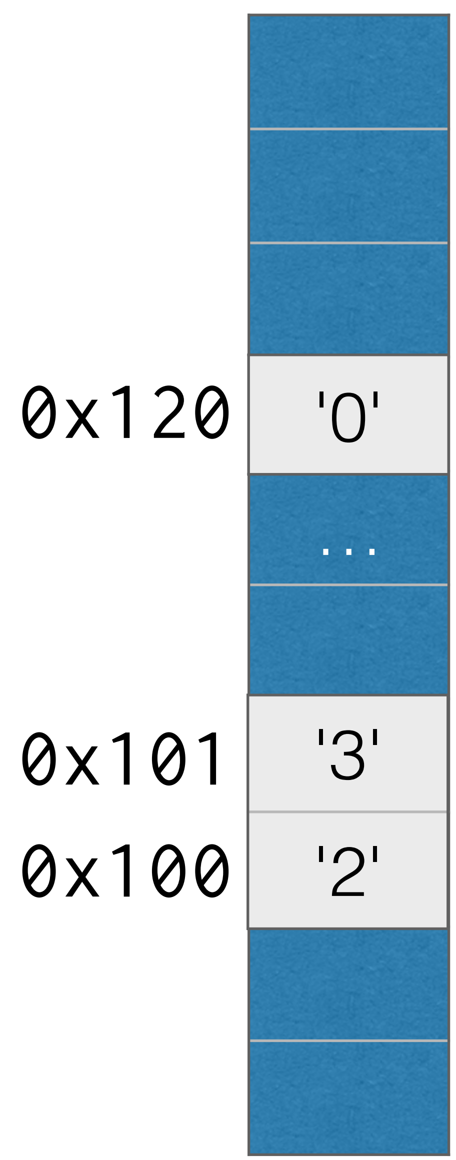
}
```

&a	0x120
b	0x100

Naive



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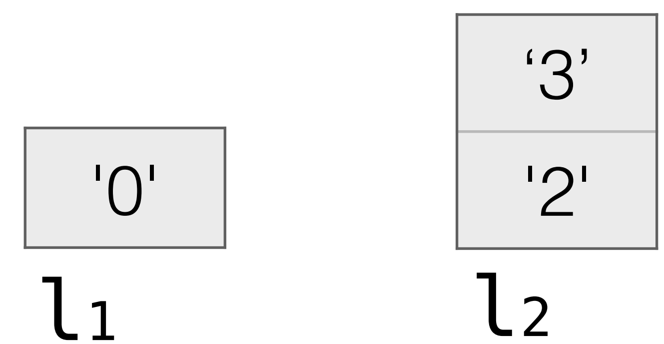

&a	$(l_1, 0)$
b	$(l_2, 0)$

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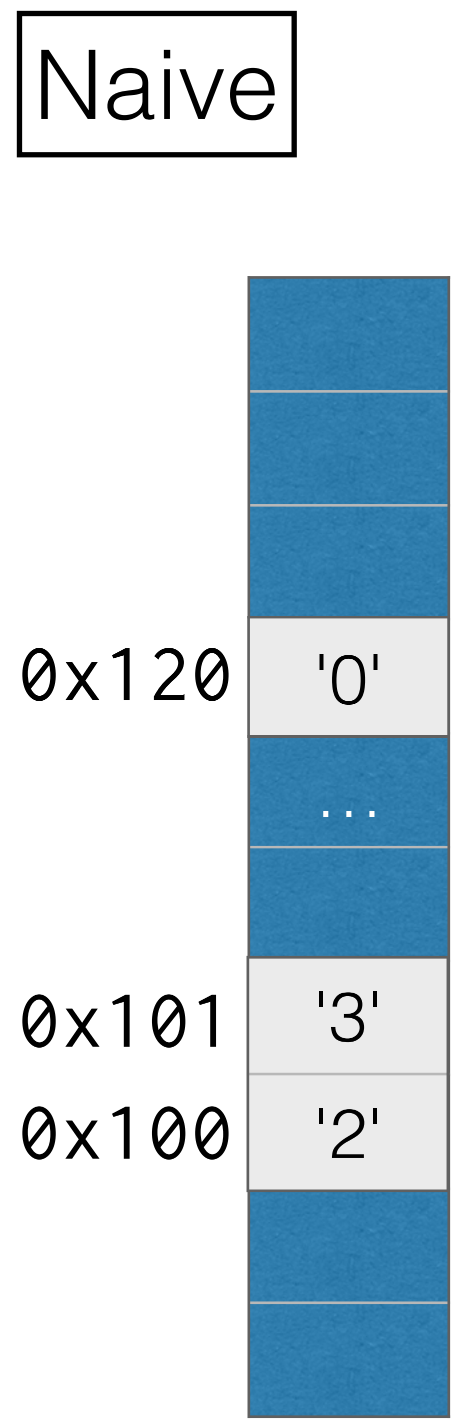
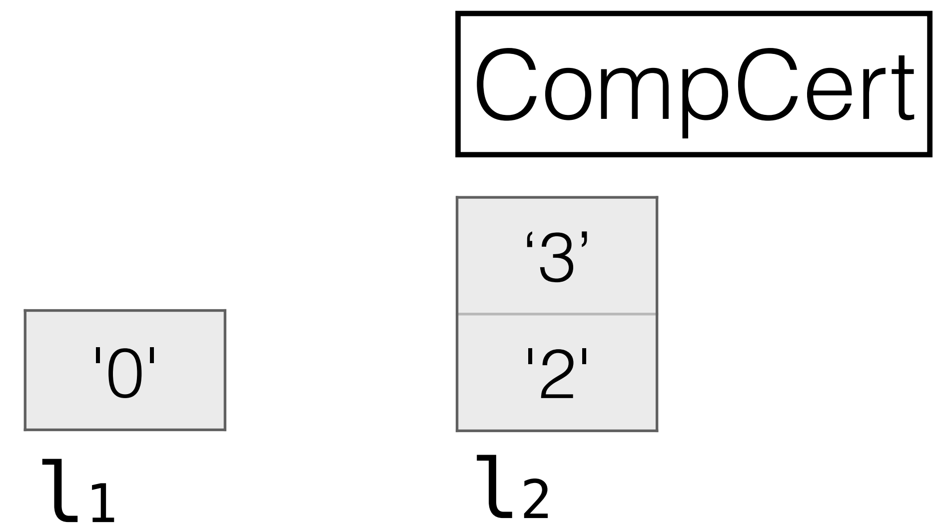
}
```



&a	0x120
b	0x100
b+0x20	0x120



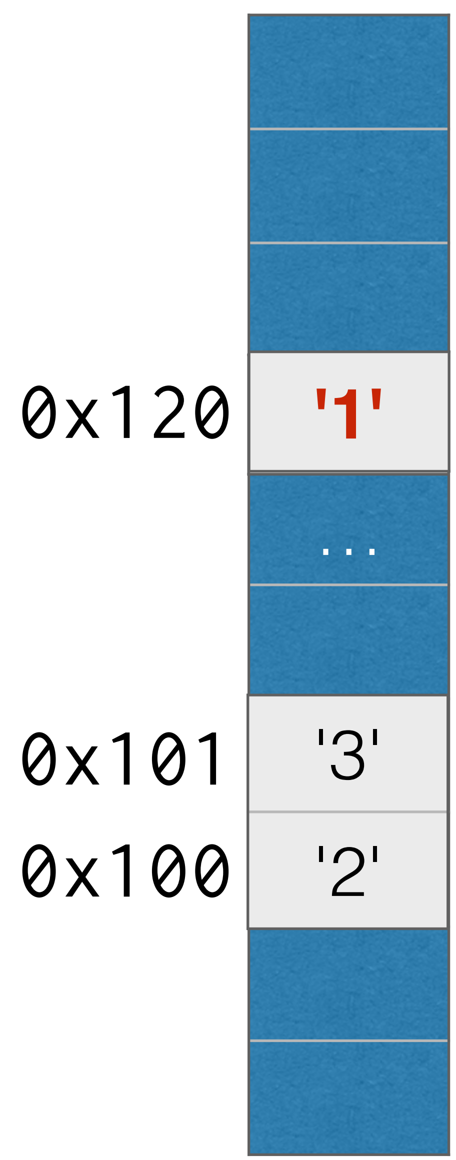
&a	$(l_1, 0)$
b	$(l_2, 0)$
b+0x20	$(l_2, 0x20)$

CompCert Model:
Protection by Logical Blocks

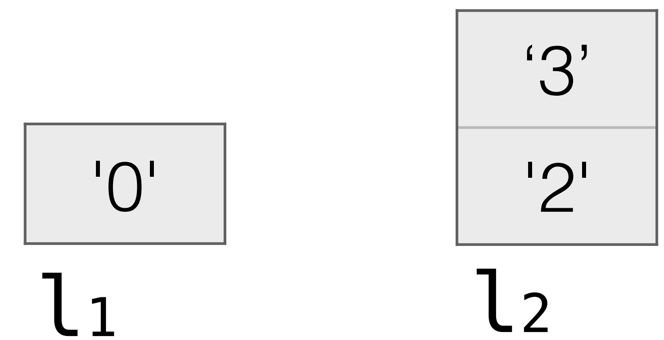
```
void g() {
 char b[2]={'2','3'};
 char* p = b + 0x20;
 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```

&a	0x120
b	0x100
b+0x20	0x120

Naive

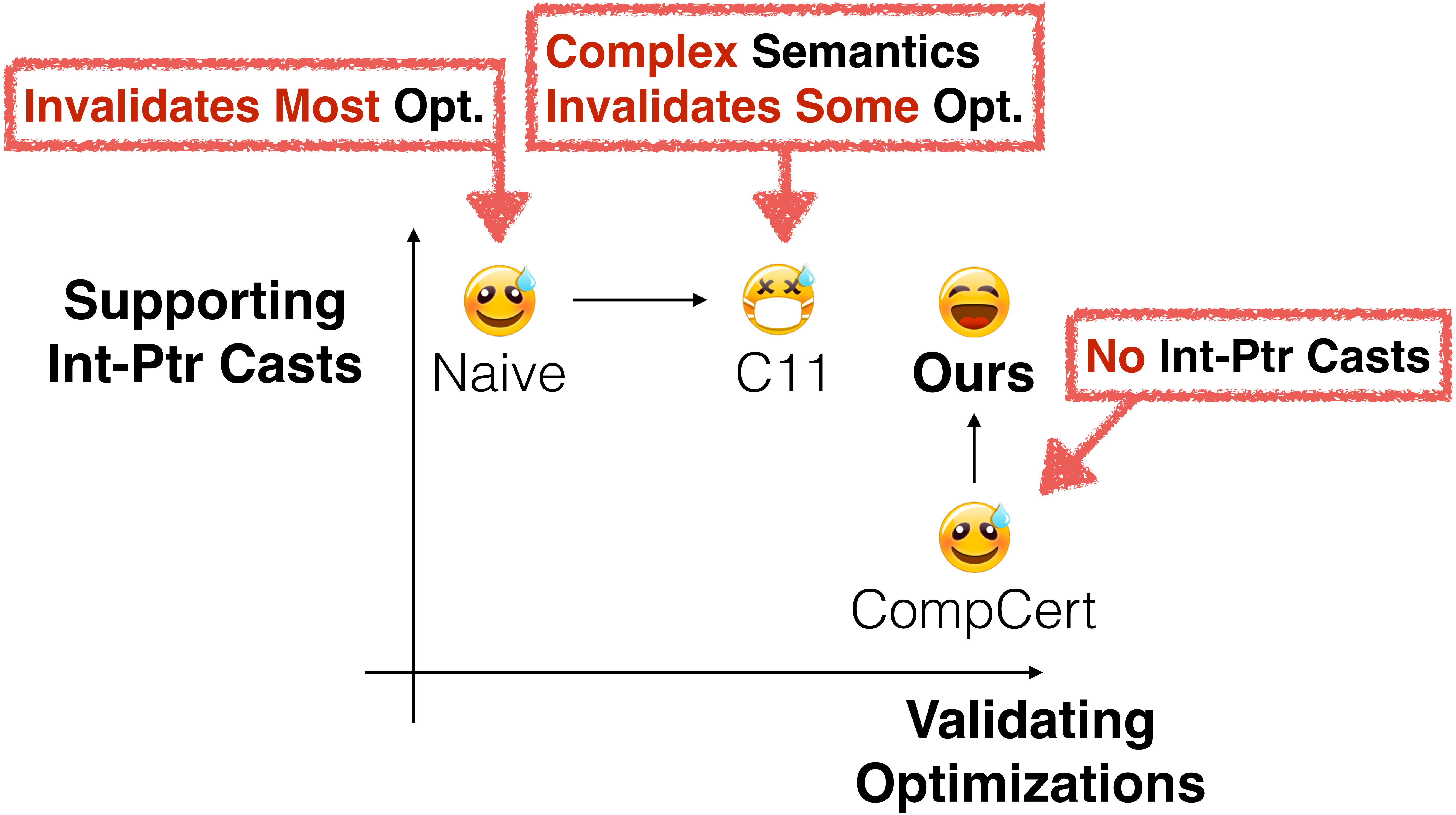


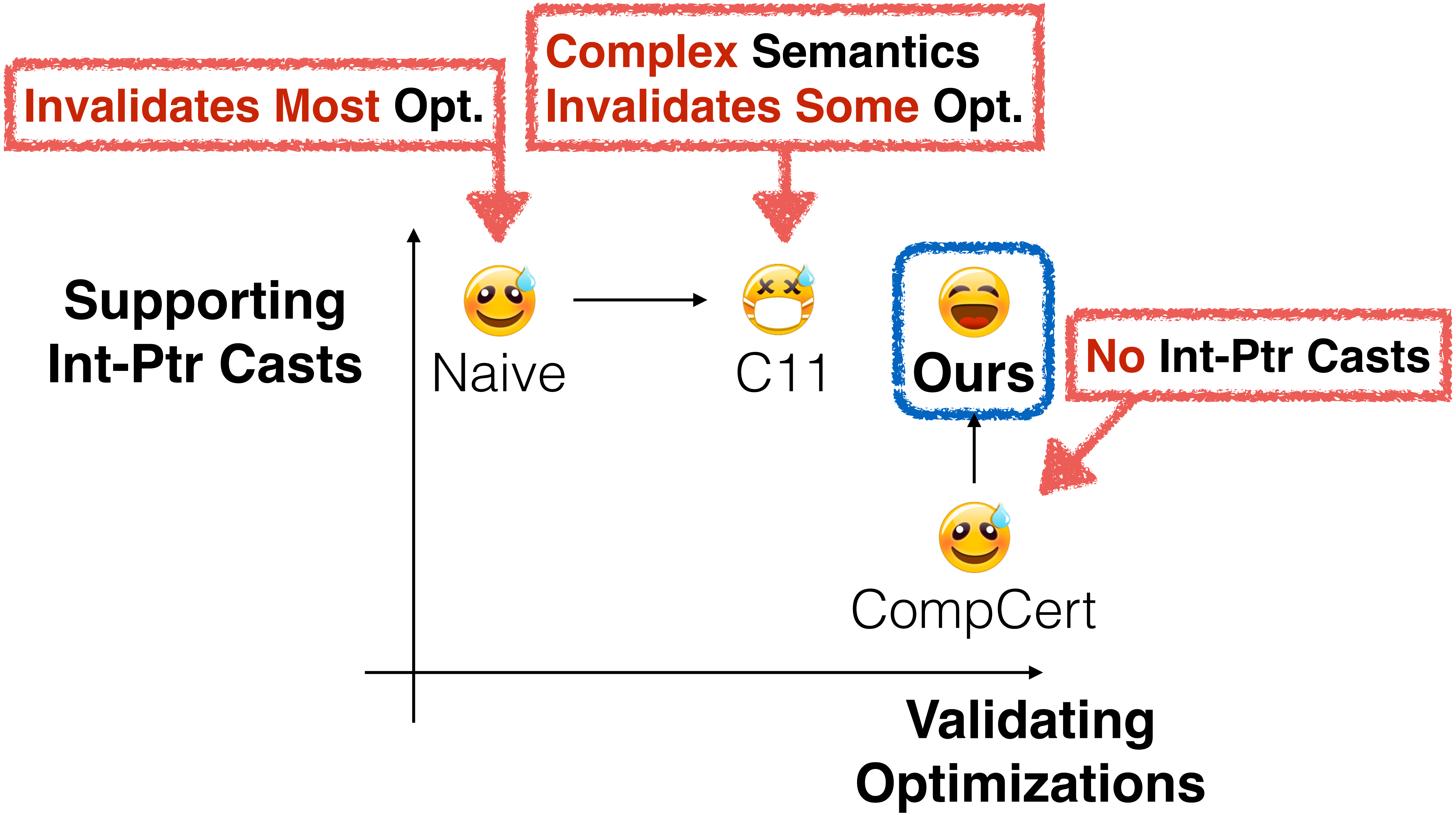
CompCert



Cannot Access a

&a	$(l_1,0)$
b	$(l_2,0)$
b+0x20	$(l_2,0x20)$


Complex Semantics
Invalidates Some Opt.
Invalidates Most Opt.
Supporting
Int-Ptr Casts
Naive
C11
Ours
No Int-Ptr Casts
CompCert
Validating
Optimizations


Invalidates Most Opt.
Complex Semantics
Invalidates Some Opt.
Supporting
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CompCert
Validating
Optimizations

Our Model:
High-Level Idea

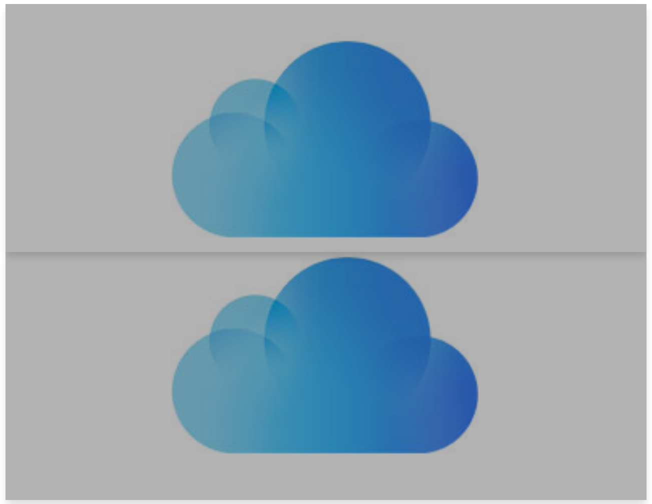
- **Pointers become integers only when casted.**

Integers

`0x120`

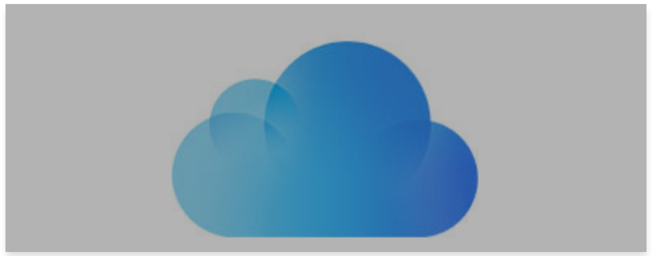
`0x100`

Pointers



Our Model:
High-Level Idea

- **Pointers** **become** **integers** **only when casted.**

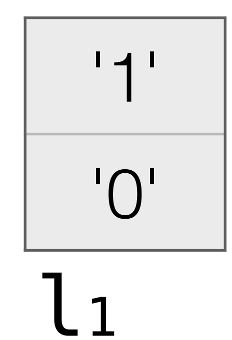
Integers	Pointers
0x120	
0x100	0x100

Our Model:
Realizes at Casting to Integer

```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```

Our Model:
Realizes at Casting to Integer

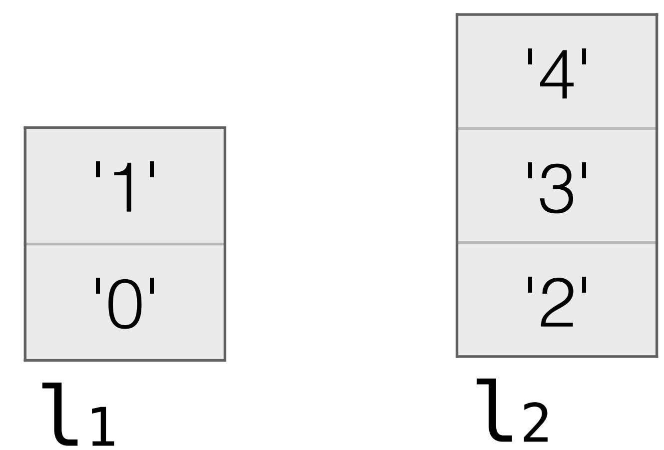
```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



a | $(l_1, 0)$

Our Model:
Realizes at Casting to Integer

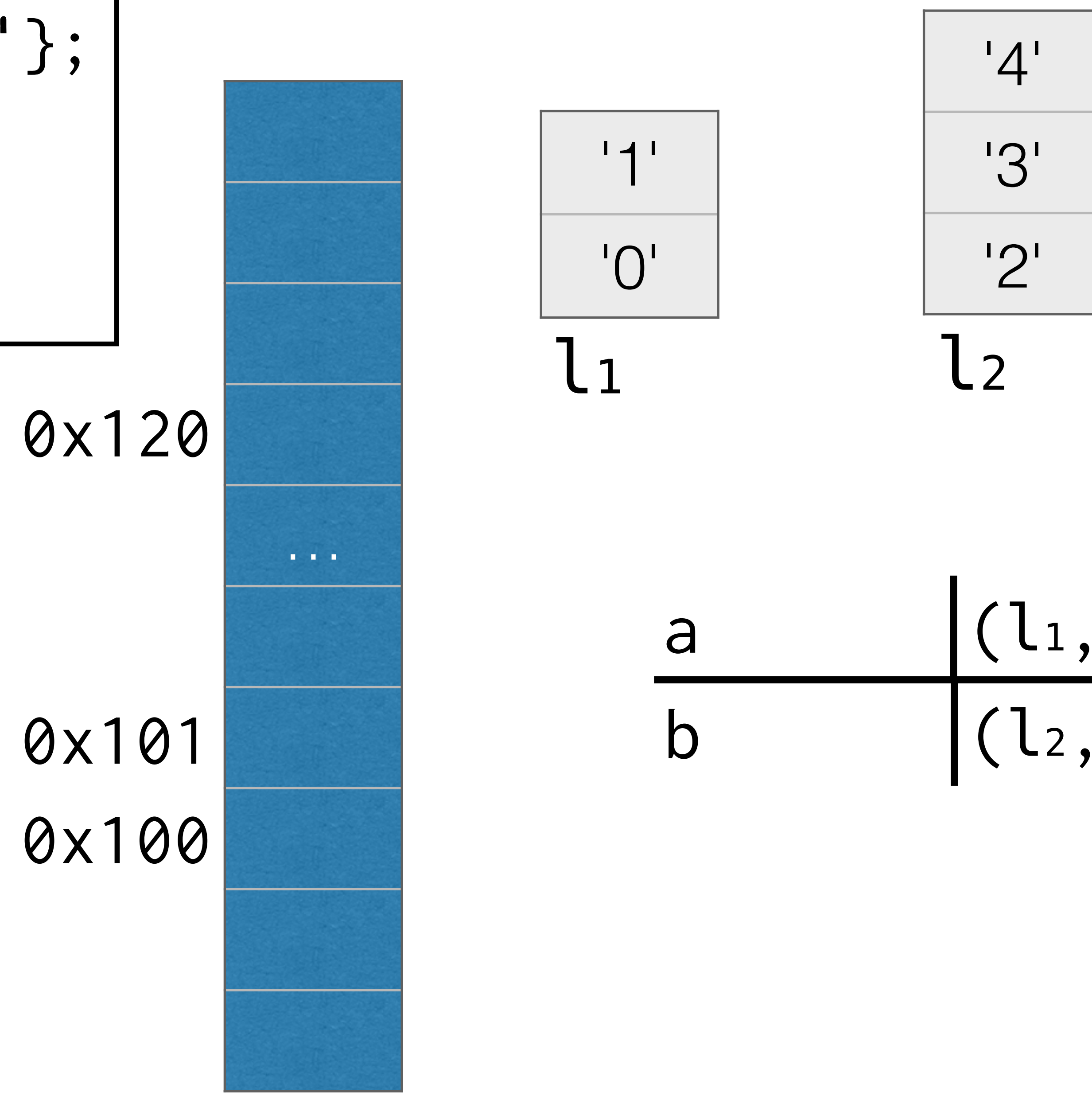
```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



a	$(l_1, 0)$
b	$(l_2, 0)$

Our Model:
Realizes at Casting to Integer

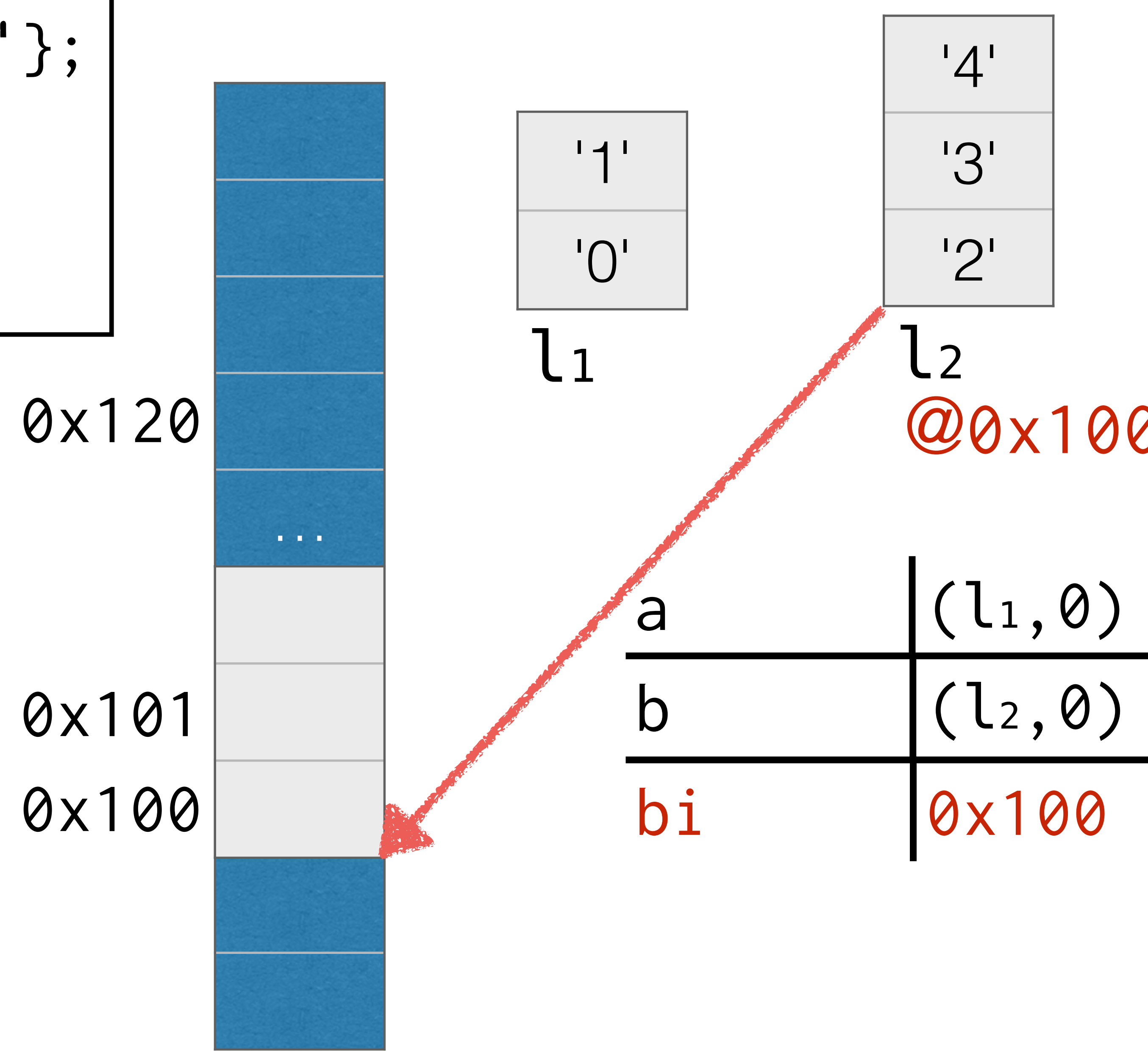
```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



a	(l1,0)
b	(l2,0)

Our Model:
Realizes at Casting to Integer

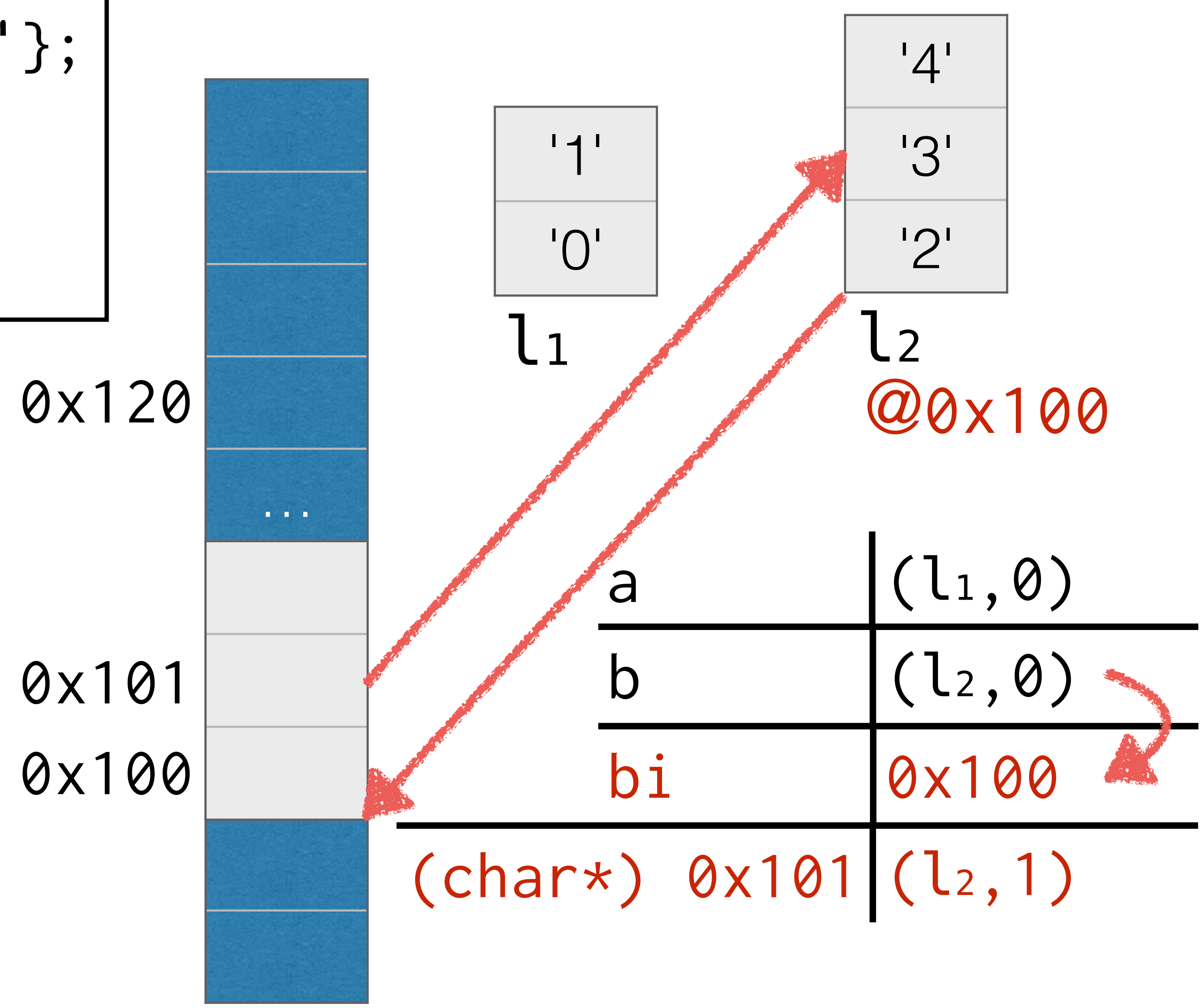
```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



a	$(l_1, 0)$
b	$(l_2, 0)$
bi	0x100

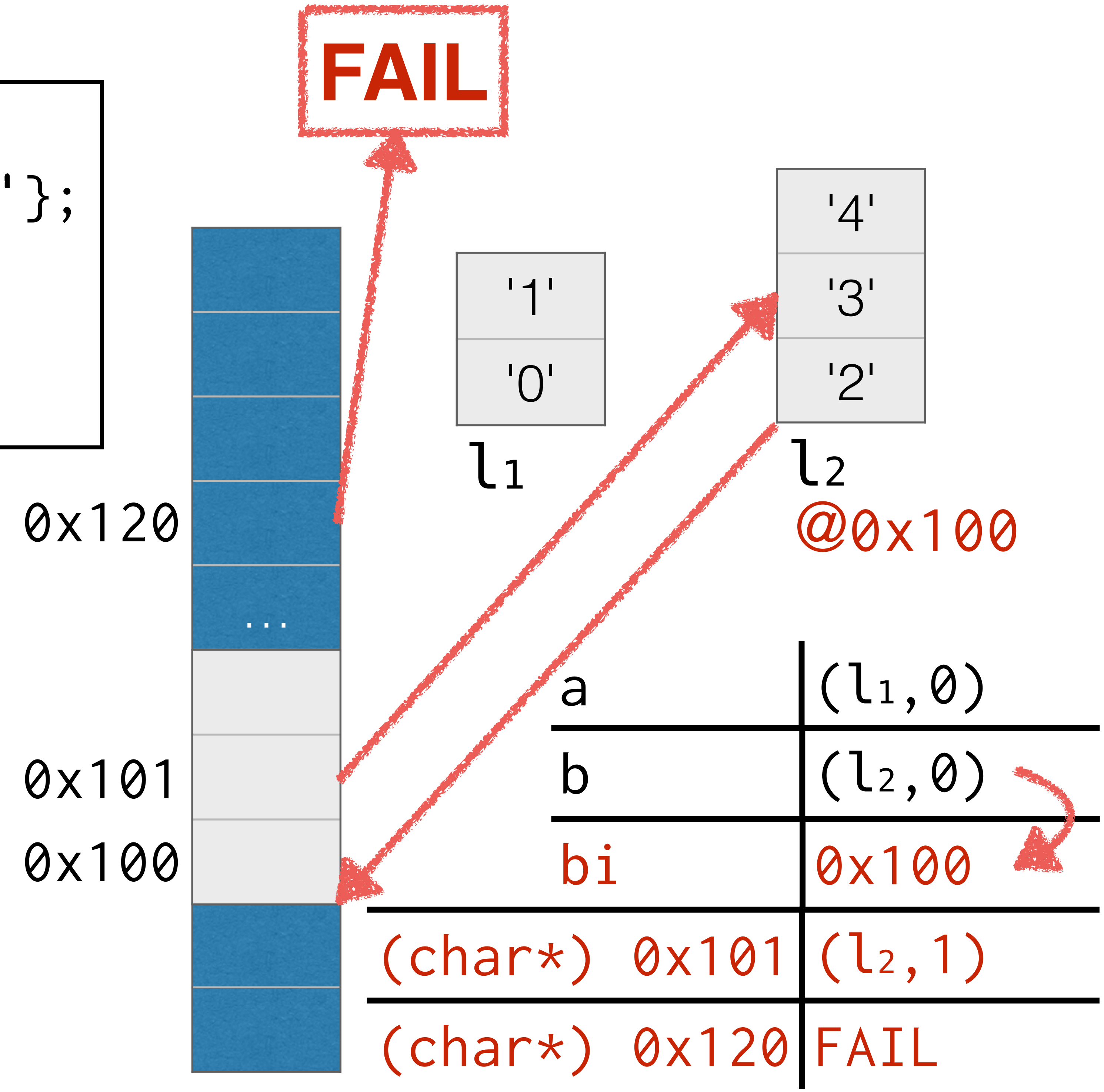
Our Model:
Realizes at Casting to Integer

```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



Our Model:
Realizes at Casting to Integer

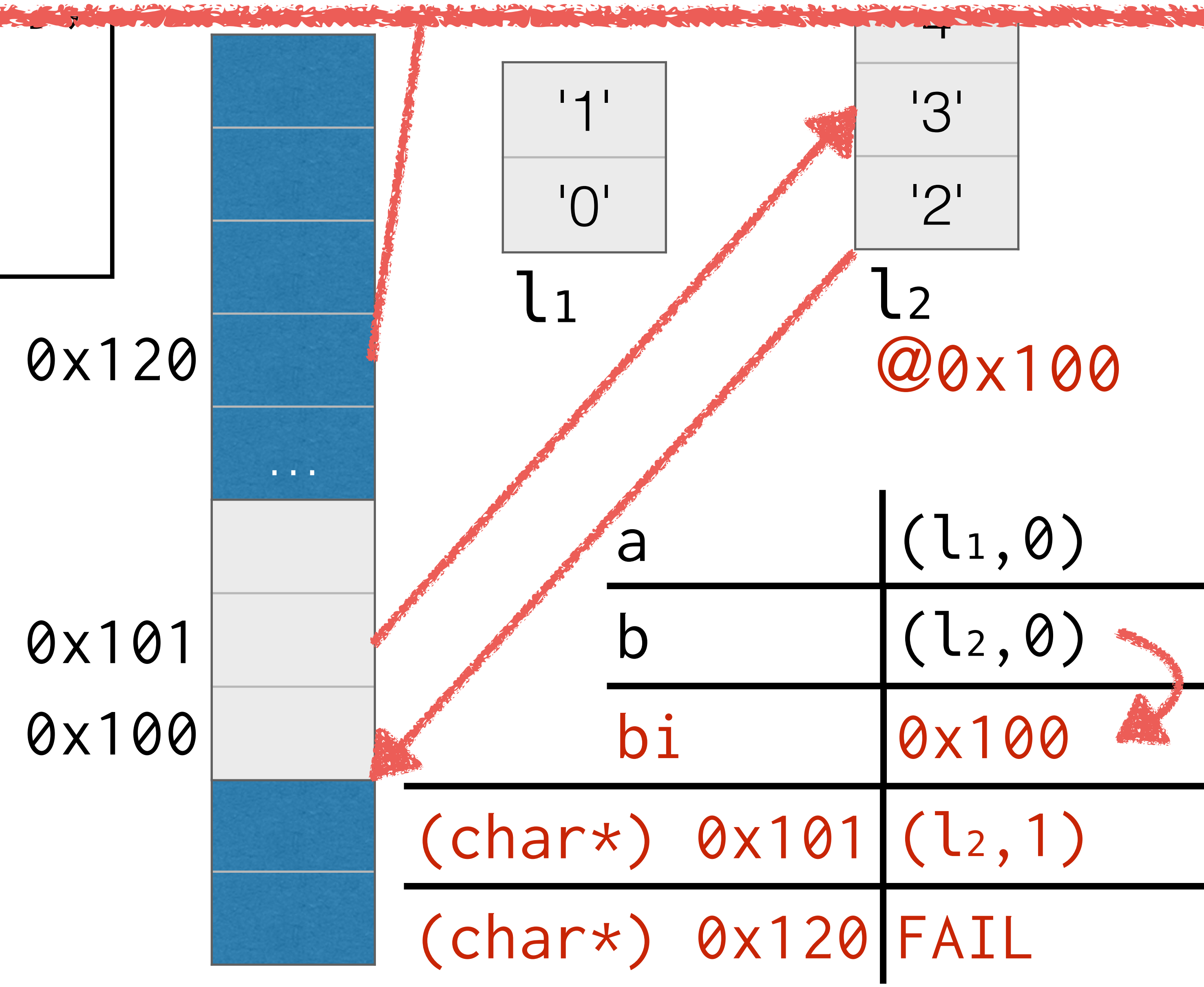
```
char a[2] = {'0','1'};
char b[3] = {'2','3','4'};
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



Our Model:

- **Realizes blocks when casting to integer**
- **Casts back to corresponding blocks**

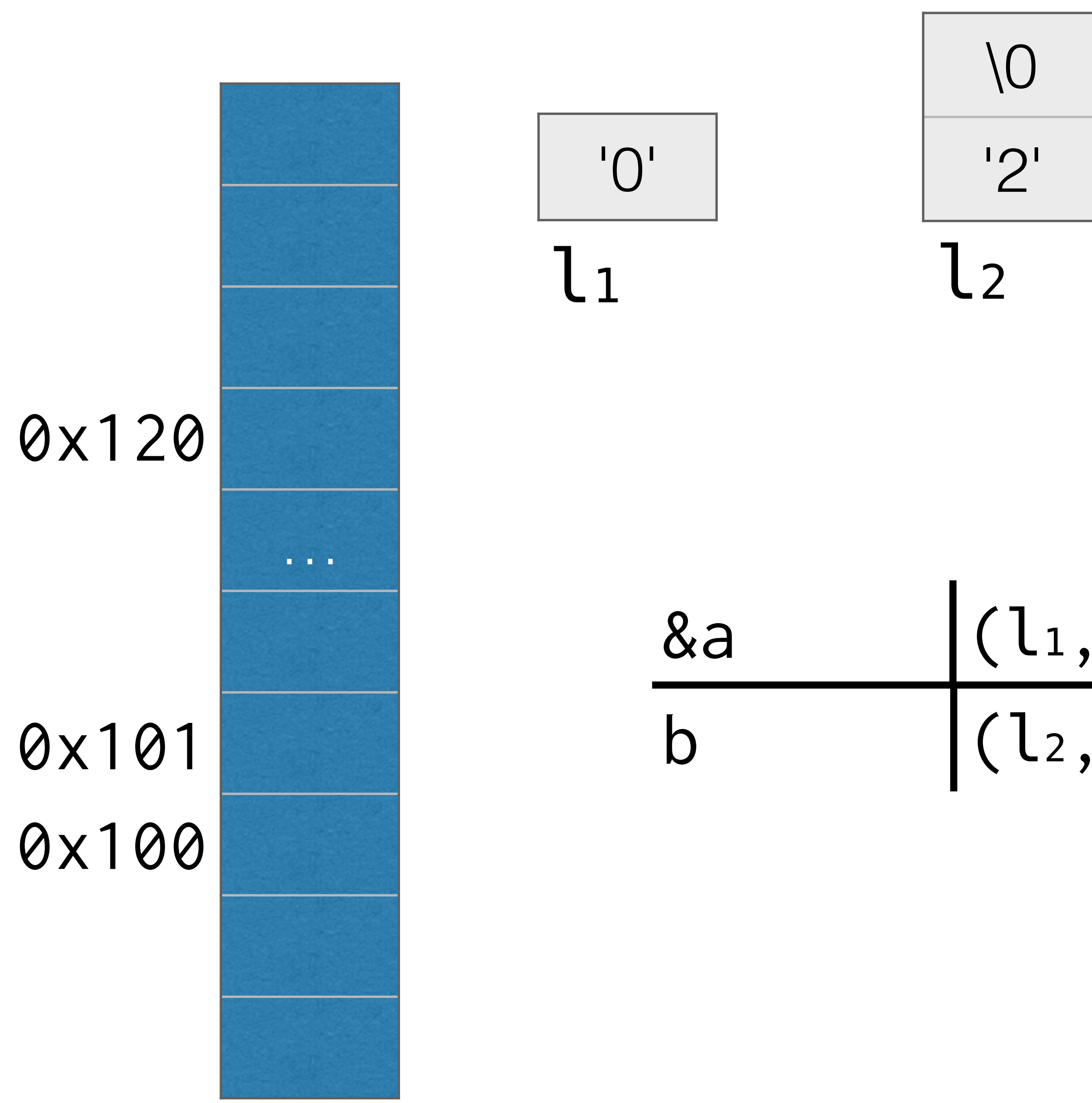
```
bi = (uintptr_t) b;
p1 = (char*) 0x101;
p2 = (char*) 0x120;
```



Benefits of Our Model (1/6):
Still Validates Optimizations

```
void g() {
 char b[2]={'2','3'};
 char* p = b + 0x20;

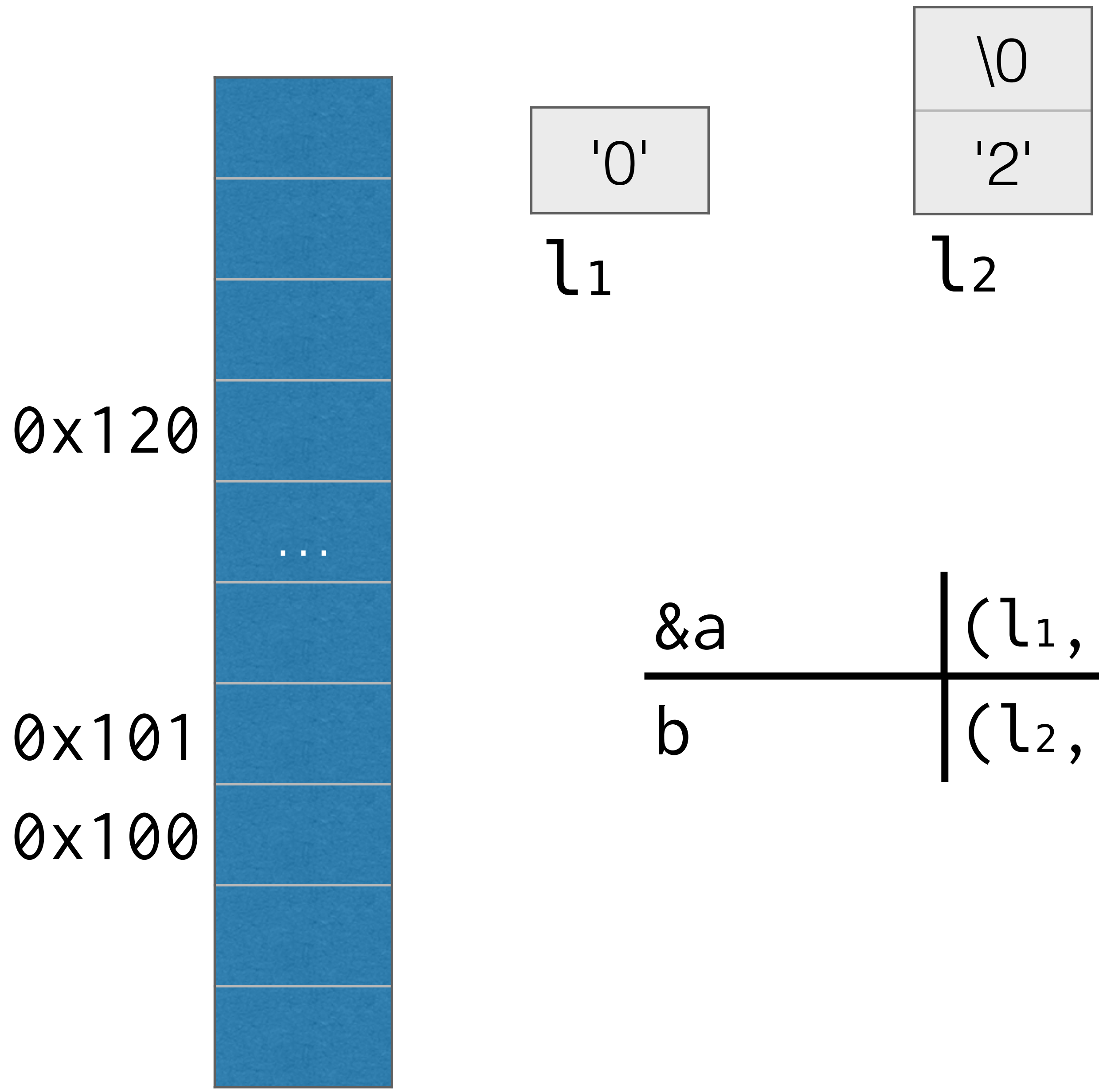

 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```



&a	$(l_1,0)$
b	$(l_2,0)$

Benefits of Our Model (1/6):
Still Validates Optimizations

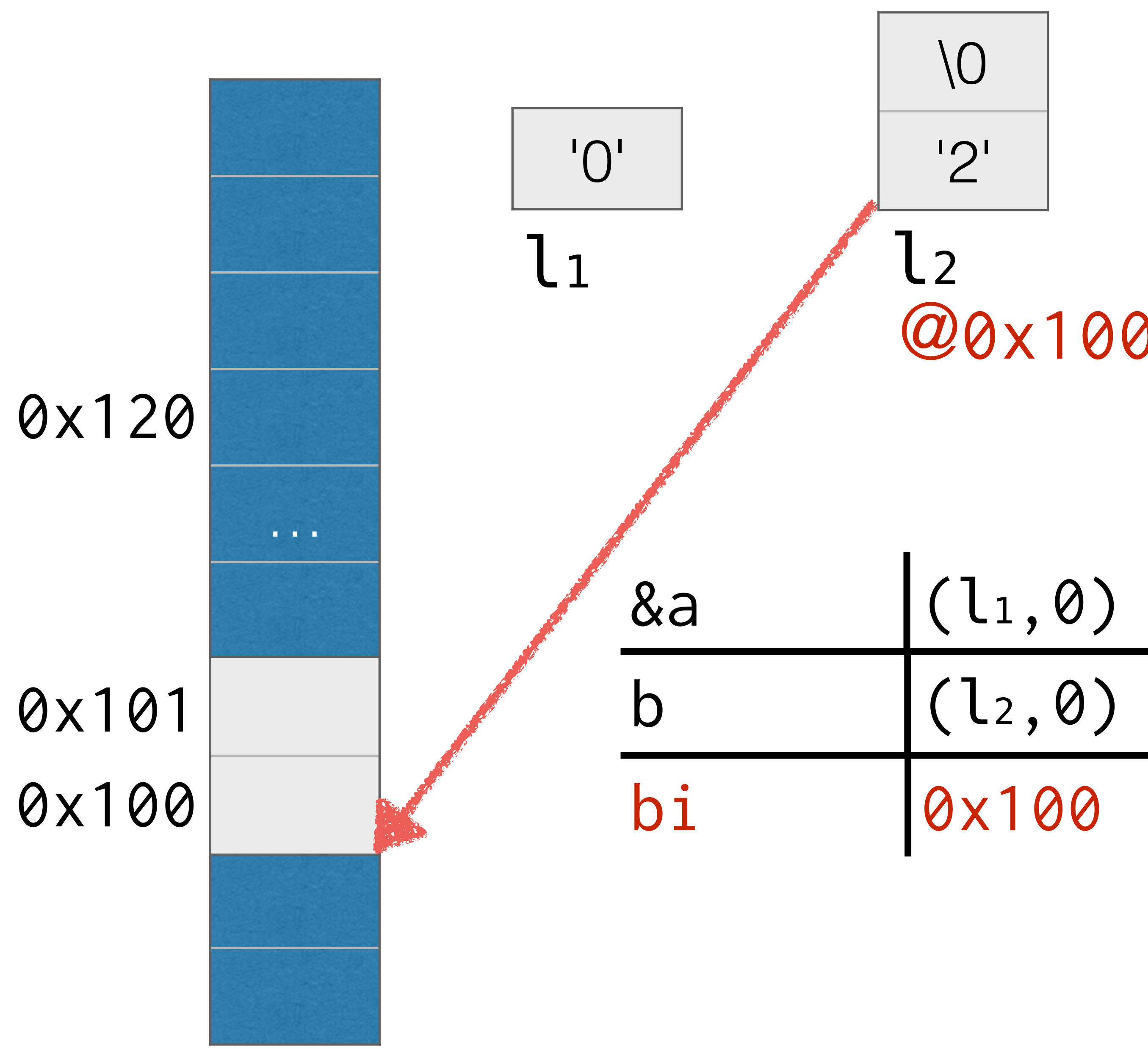
```
void g() {
 char b[2]={'2','3'};
 //char* p = b + 0x20;
 bi = (uintptr_t) b;
 p = (char*) (bi+0x20);
 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```



&a	$(l_1, 0)$
b	$(l_2, 0)$

Benefits of Our Model (1/6):
Still Validates Optimizations

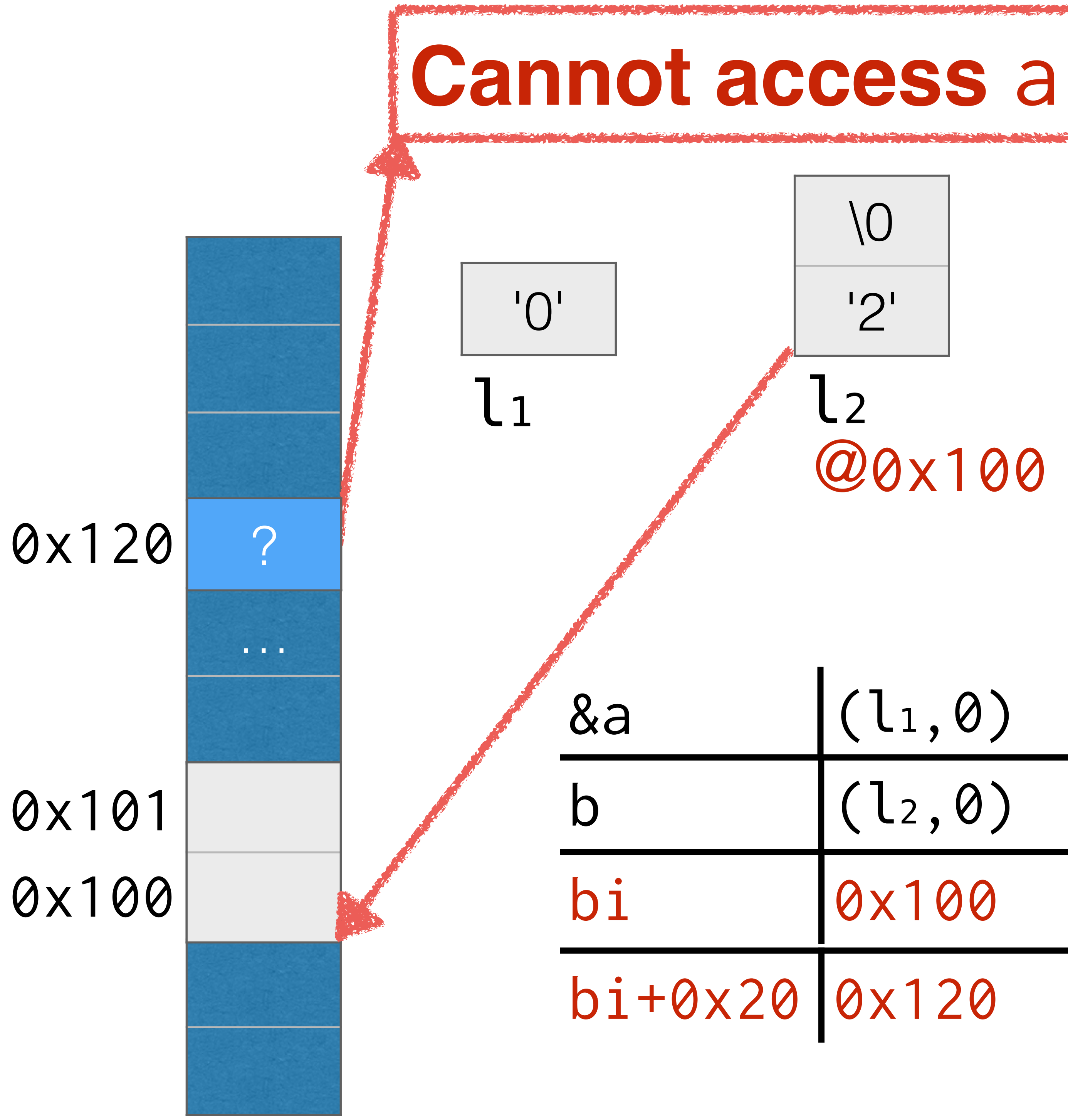
```
void g() {
 char b[2]={'2','3'};
 //char* p = b + 0x20;
 bi = (uintptr_t) b;
 p = (char*) (bi+0x20);
 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```



&a	(l1,0)
b	(l2,0)
bi	0x100

Benefits of Our Model (1/6):
Still Validates Optimizations

```
void g() {
 char b[2]={'2','3'};
 //char* p = b + 0x20;
 bi = (uintptr_t) b;
 p = (char*) (bi+0x20);
 *p = '1';
}
char f() {
 char a = '0';
 g();
 return a; // -> '0'
}
```



&a	(l1,0)
b	(l2,0)
bi	0x100
bi+0x20	0x120

Benefits of Our Model (2/6):
Fully Supports Integer-Pointer Casts

- **Pointer-to-integer casts always succeed.**
- **Integer operations on casted pointers always succeed.**

Benefits of Our Model (3/6): Simple Semantics

- **Integer values are just integers w/o permission.**
- **Integer operations are just integer operations.**

Benefits of Our Model (4/6): More Optimizations

- **Integer optimizations are allowed.**

```
int a = x - x; // -> int a = 0;
```

- **The useful code motion is allowed.**

```
int a, b;
…
if (a != b) {
  a = b;
}
```

```
int a, b;
…
if (a != b) {
}
a = b;
```

Benefits of Our Model (5/6): Easily Applicable to Compilers

- **Just treat "casted pointers as escaped".**

DEAD CODE

```
void main() {
  int x = 0;
  uintptr_t xi = (uintptr_t) &x;
  uintptr_t i;
  for (i = 0; i < xi; ++i) {}
  if (xi != i) {
    printf("unreachable\n");
  }
  xi = i; // code motion
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", x); } // prints 1
```

Benefits of Our Model (5/6):
Easily Applicable to Compilers

- **Just treat "casted pointers as escaped".**

DEAD
CODE

```
void main() {
  int x = 0;
  uintptr_t xi = (uintptr_t) &x;
  uintptr_t i;
  for (i = 0; i < xi; ++i) {}
  if (xi != i) {
    printf("unreachable\n");
  }
  xi = i; // code motion
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", x); } // prints 1
```

treated as escaped

Benefits of Our Model (5/6): Easily Applicable to Compilers

- **Just treat "casted pointers as escaped".**

```
void main() {
  int x = 0;
  uintptr_t xi = (uintptr_t) &x;
  uintptr_t i;
  for (i = 0; i < xi; ++i) {}
  if (xi != i) {
    printf("unreachable\n");
  }
  xi = i; // code motion
  int* p = (int*) xi;
  *p = 1;
  printf("%d\n", x); } // prints 1
```

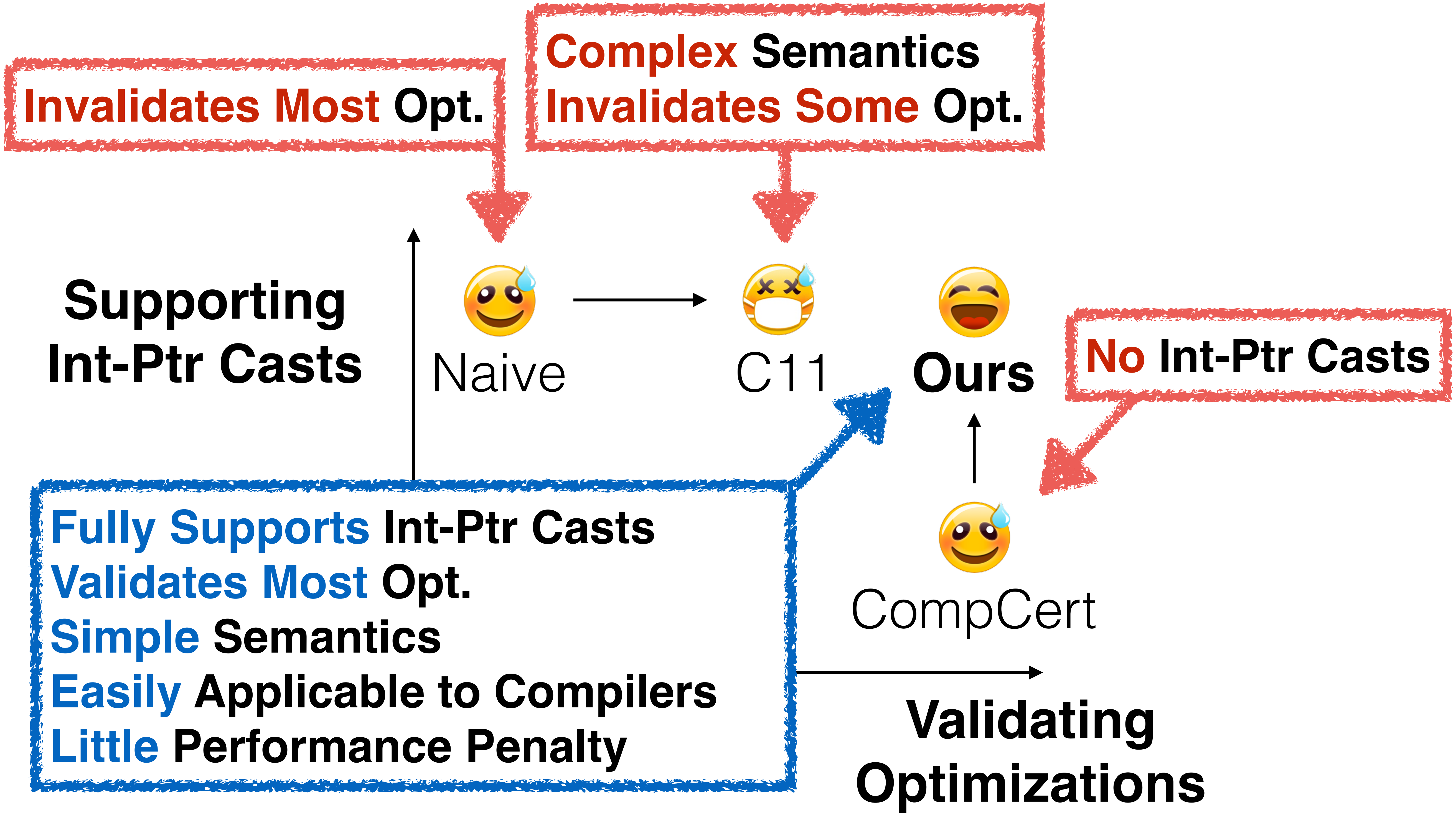
DEAD CODE

treated as escaped

no constant propagation

Benefits of Our Model (6/6):
Little Performance Penalty

- **Insignificant: performance degradation due to "casted pointers as escaped"**
  - In practice, addresses casted to integers are **global addresses**.
  - Compilers **already** treat **global addresses as escaped**.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What Else is in the Paper?

- **Formal definition of our memory model**
- **Reasoning principles for compiler verification**
- **Verification of other optimization examples**
  - Dead code elim., dead allocation elim., arithmetic optimizations, alias analysis, etc.
- **Comparison with other possible models**

Fully formalized in Coq