TOWARDS SAFETY & SECURITY IN C++

Daniela Engert - using std::c++ 2025

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C-00000291*.sys

SOFTWARE VULNERABILITIES

- security and safety
- safety in our code, or lack thereof
- existing solutions for improvement
- new features in C++26
- options for the future

ABOUT ME

- Electrical engineer
- I build computers and create software for more than 40 years
- I develop hardware and software in the field of applied digital signal processing for more than 35 years

- I'm a member of the C++ committee (learning novice) for 5 years (EWG, SG15)

SOFTWARE VULNERABILITIES

- About 70 percent of Microsoft common vulnerabilities and exposures (CVEs) are memory safety vulnerabilities (based on 2006-2018 CVEs).[8]
- About 70 percent of vulnerabilities identified in Google's Chromium project are memory safety vulnerabilities.[9]
- In an analysis of Mozilla vulnerabilities, 32 of 34 critical/high bugs were memory safety vulnerabilities.[10]
- Based on analysis by Google's Project Zero team, 67 percent of zero-day vulnerabilities in 2021 were memory safety vulnerabilities.[11]

The Case for Memory Safe Roadmaps, 2023

2024 CWE Top 25

Rank	ID	Name	Score	CVEs in KEV	Rank Change vs. 2023
1	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	56.92	3	+1
2	CWE-787	Out-of-bounds Write	45.20	18	-1
3	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	35.88	4	0
4	CWE-352	Cross-Site Request Forgery (CSRF)	19.57	0	+5
5	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	12.74	4	+3
6	CWE-125	Out-of-bounds Read	11.42	3	+1
7	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	11.30	5	-2
8	CWE-416	Use After Free	10.19	5	-4
9	CWE-862	Missing Authorization	10.11	0	+2
10	CWE-434	Unrestricted Upload of File with Dangerous Type	10.03	0	0
11	CWE-94	Improper Control of Generation of Code ('Code Injection')	7.13	7	+12
12	CWE-20	Improper Input Validation	6.78	1	-6
13	CWE-77	Improper Neutralization of Special Elements used in a Command ('Command Injection')	6.74	4	+3
14	CWE-287	Improper Authentication	5.94	4	-1
15	CWE-269	Improper Privilege Management	5.22	0	+7
16	CWE-502	Deserialization of Untrusted Data	5.07	5	-1
17	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	5.07	0	+13
18	CWE-863	Incorrect Authorization	4.05	2	+6
19	CWE-918	Server-Side Request Forgery (SSRF)	4.05	2	0
20	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	3.69	2	-3
21	CWE-476	NULL Pointer Dereference	3.58	0	-9
22	CWE-798	Use of Hard-coded Credentials	3.46	2	-4
23	CWE-190	Integer Overflow or Wraparound	3.37	3	-9
24	CWE-400	Uncontrolled Resource Consumption	3.23	0	+13
25	CWE-306	Missing Authentication for Critical Function	2.73	5	-5

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[redacted] now

[redacted]@pony.social

[redacted]

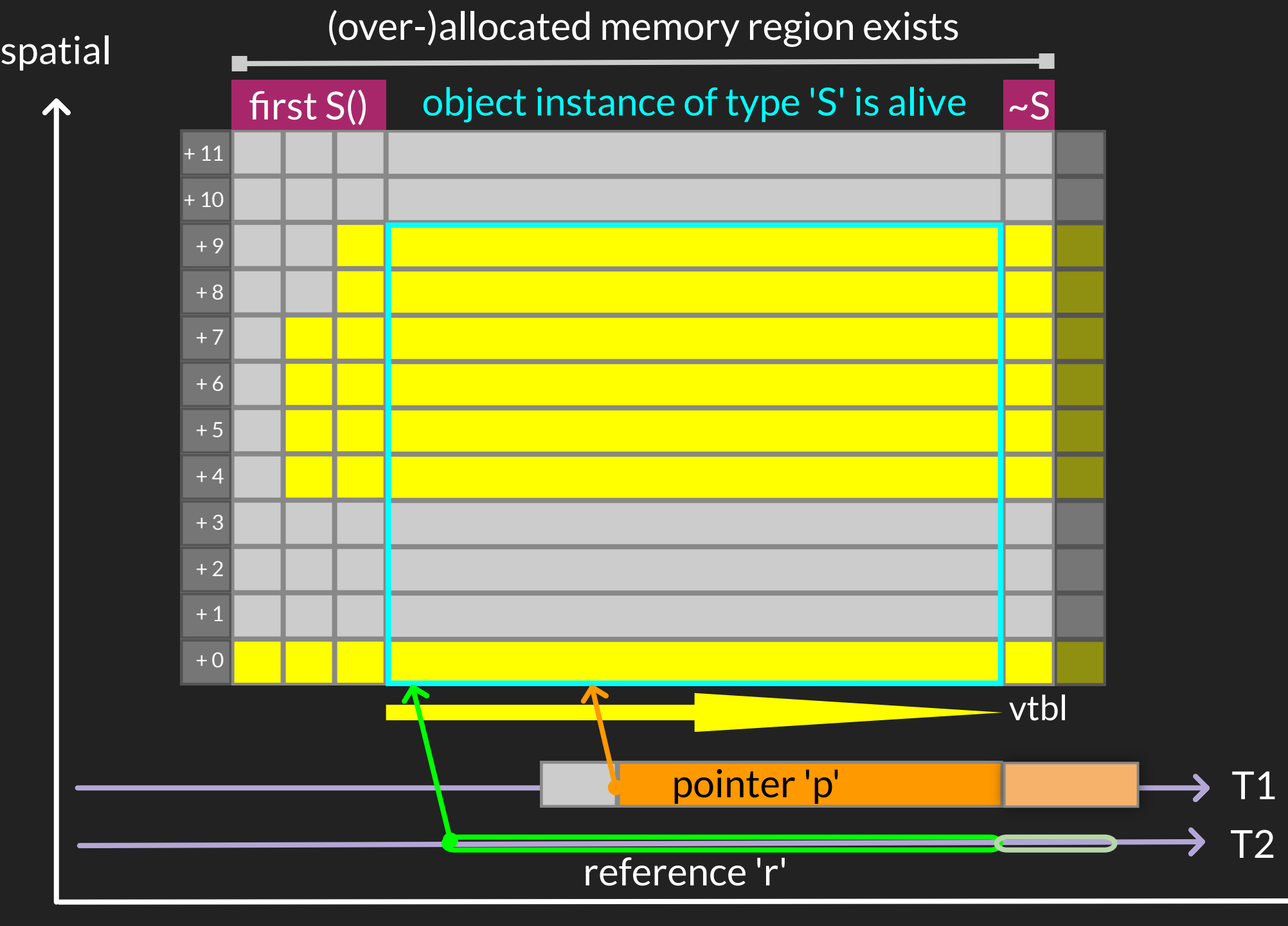
memory unsafety may cause a lot of software crashes, but it also helps a lot of people jailbreak their game consoles, so, it;s impossible to say if its bad or not,

Somewhere on Mastodon...

OH MY, ALL THOSE 'SAFETIES' !

- Language Safety
- Spatial Safety
- Temporal Safety
- Type Safety
- Bounds Safety
- Memory Safety
- Lifetime Safety
- Thread Safety
- Functional Safety
- Occupational Safety
- Traffic/Road Safety
- Industrial Safety
- Undefined Behaviour
- Correctness
- Regulation
- Security
- etc…


DEFINITIONS




```
1  struct S {
2    S();
3    virtual ~S();
4
5    char    a = 1;
6    int32_t b = 2;
7    int16_t c = 3;
8  };
9
10 auto _ = new S;
11
12 void Thread1 {
13   S * p;
14   ...
15   p = _;
16   ...
17 }
18
19 void Thread2 {
20   ...
21   S & r = *_;
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23 }
```

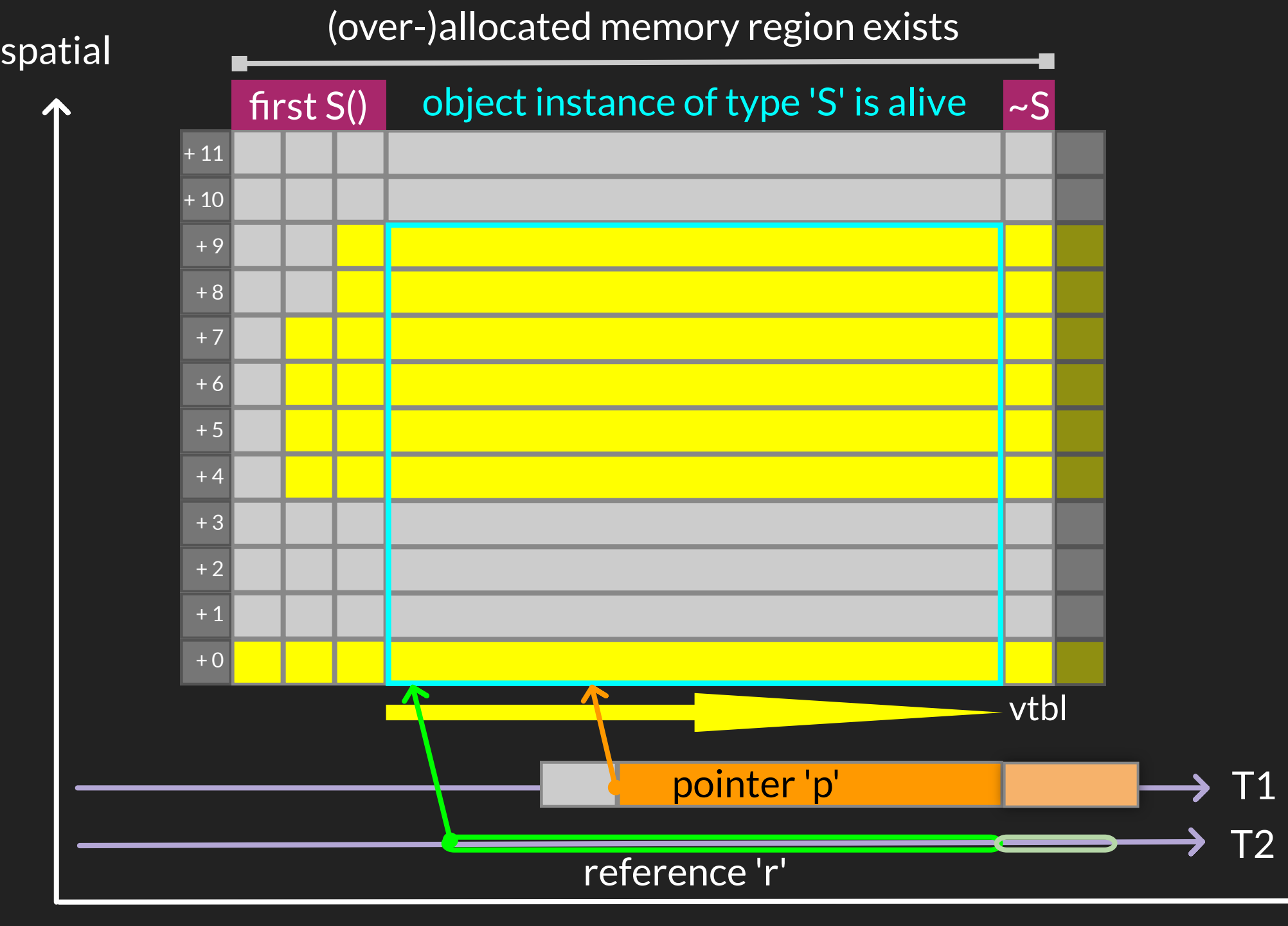


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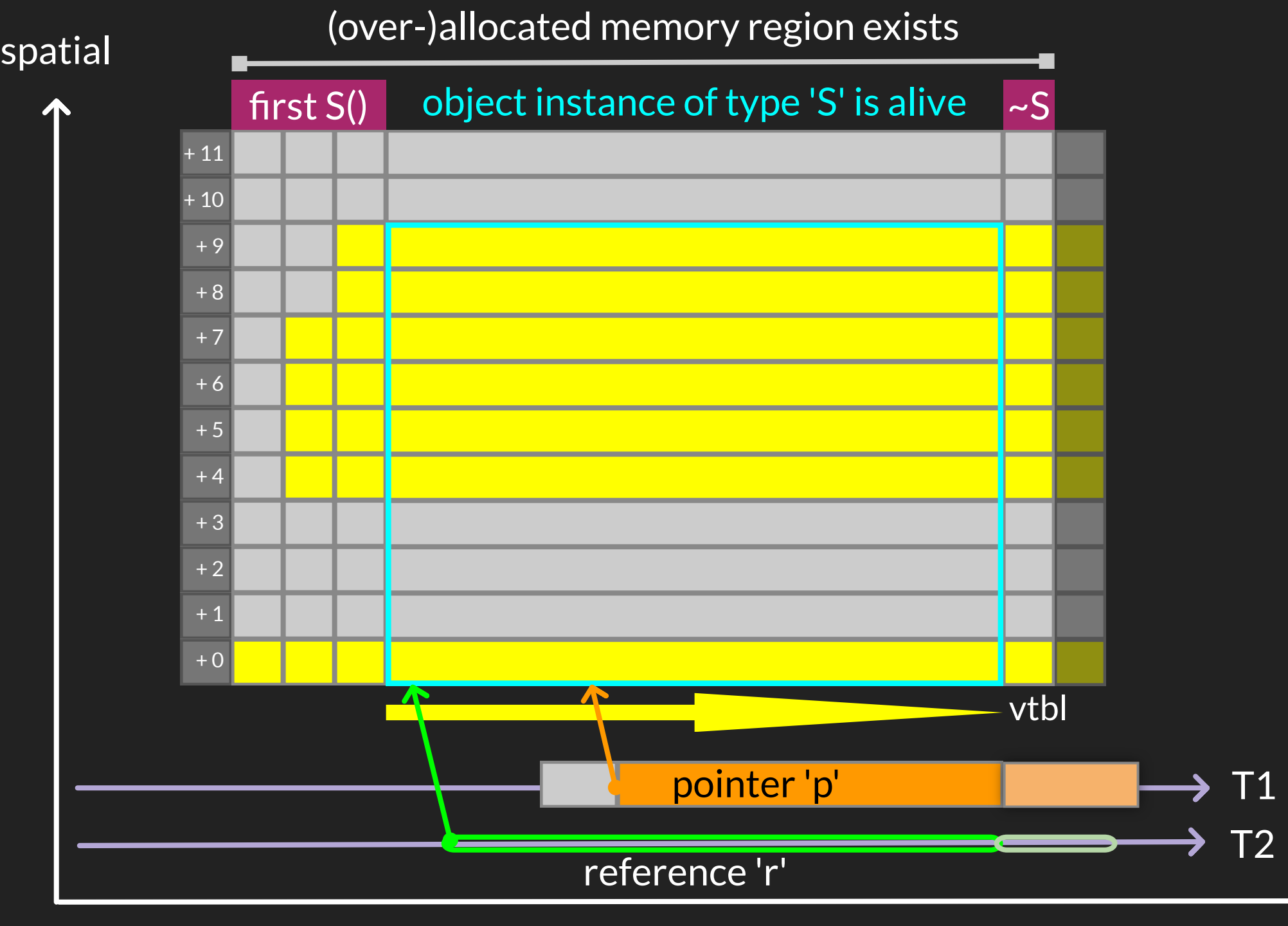


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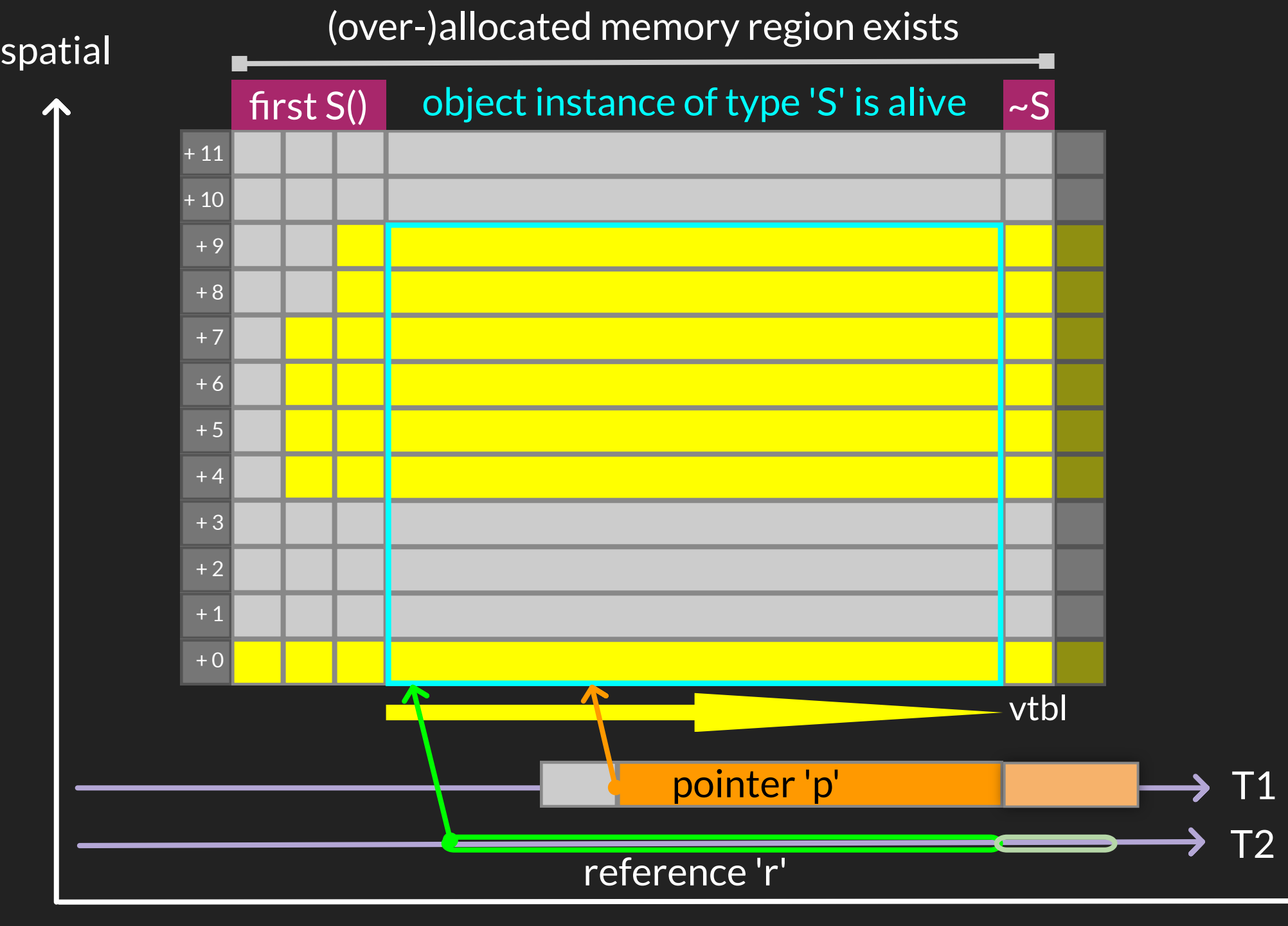


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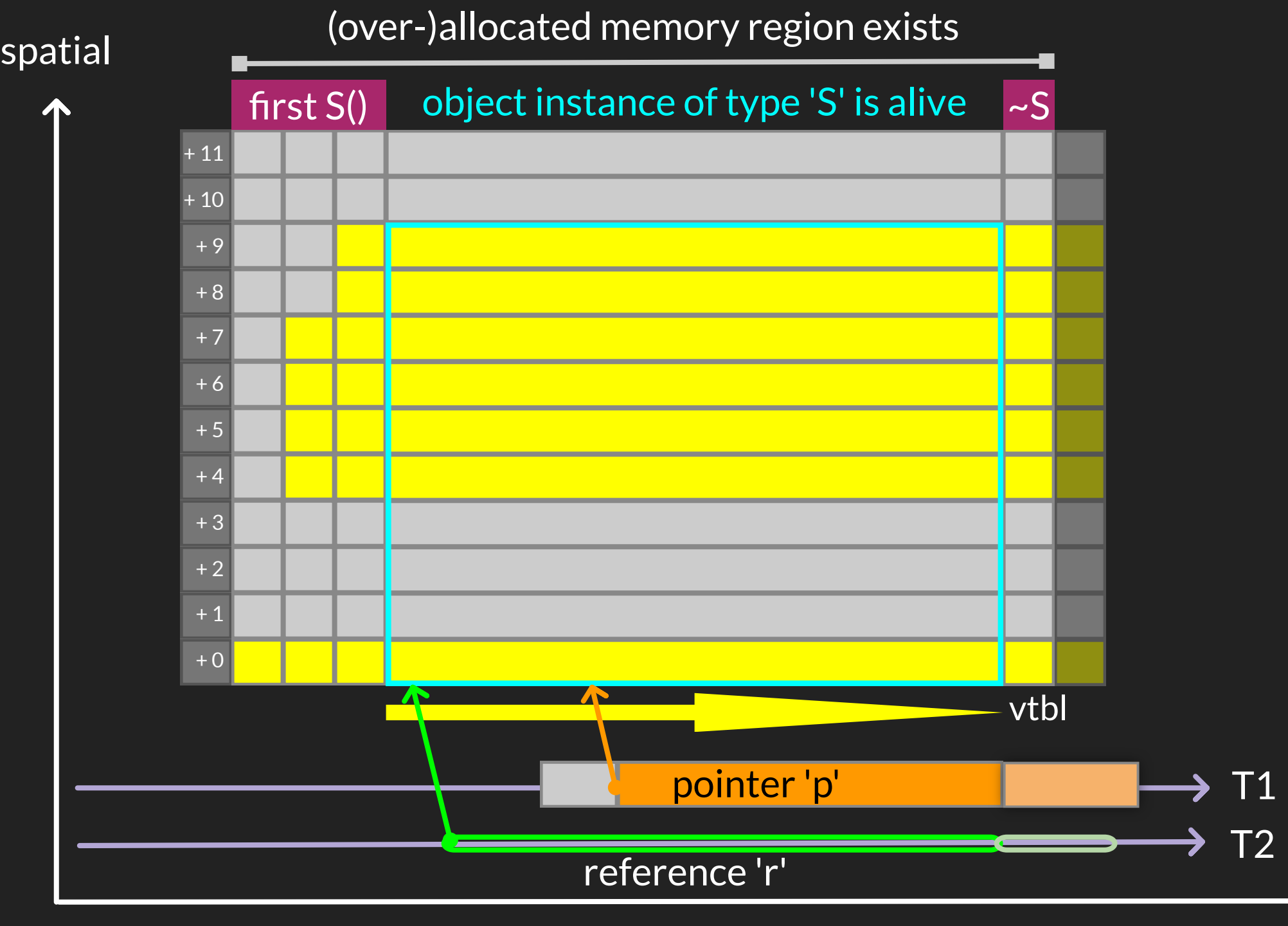


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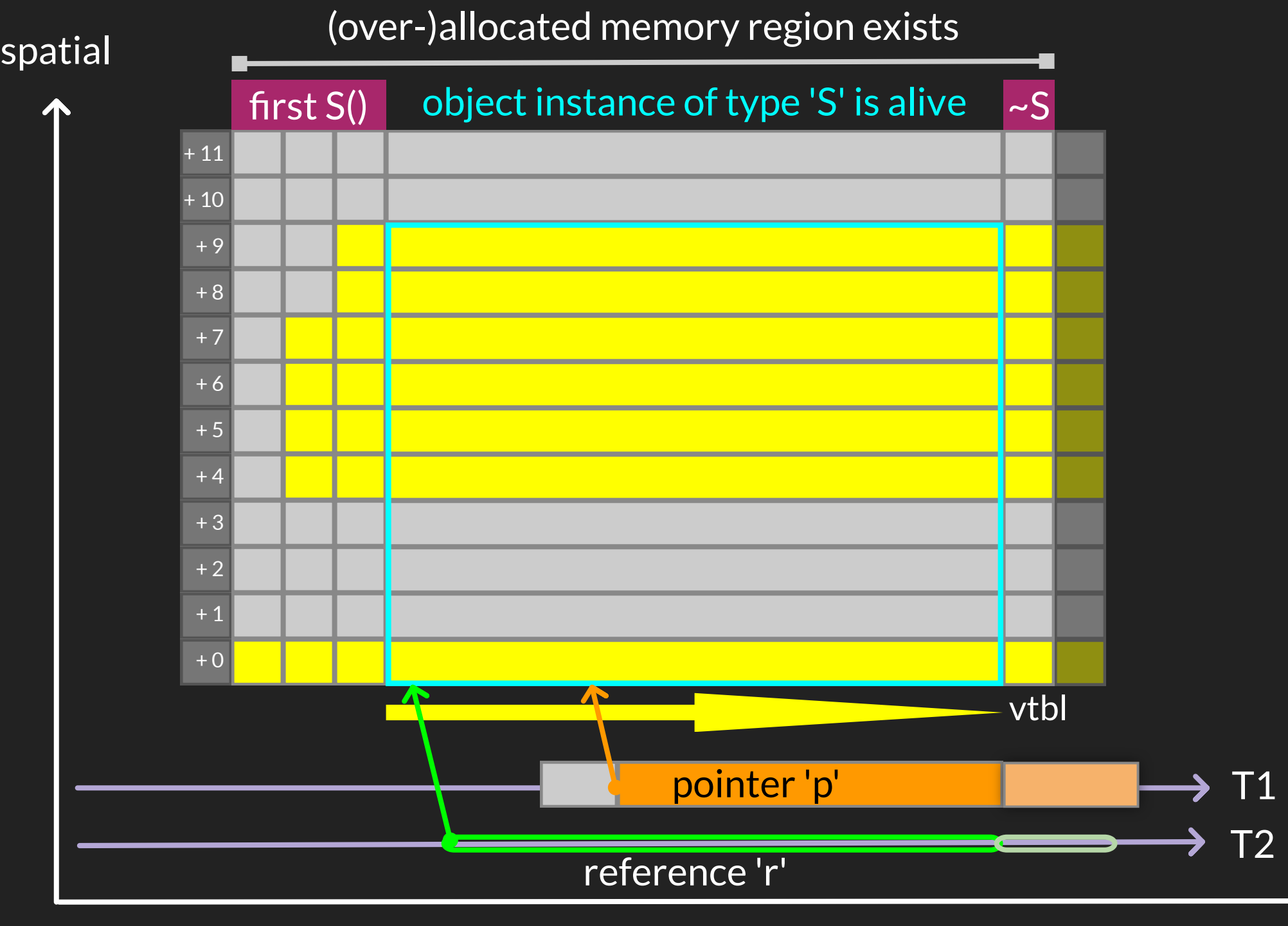


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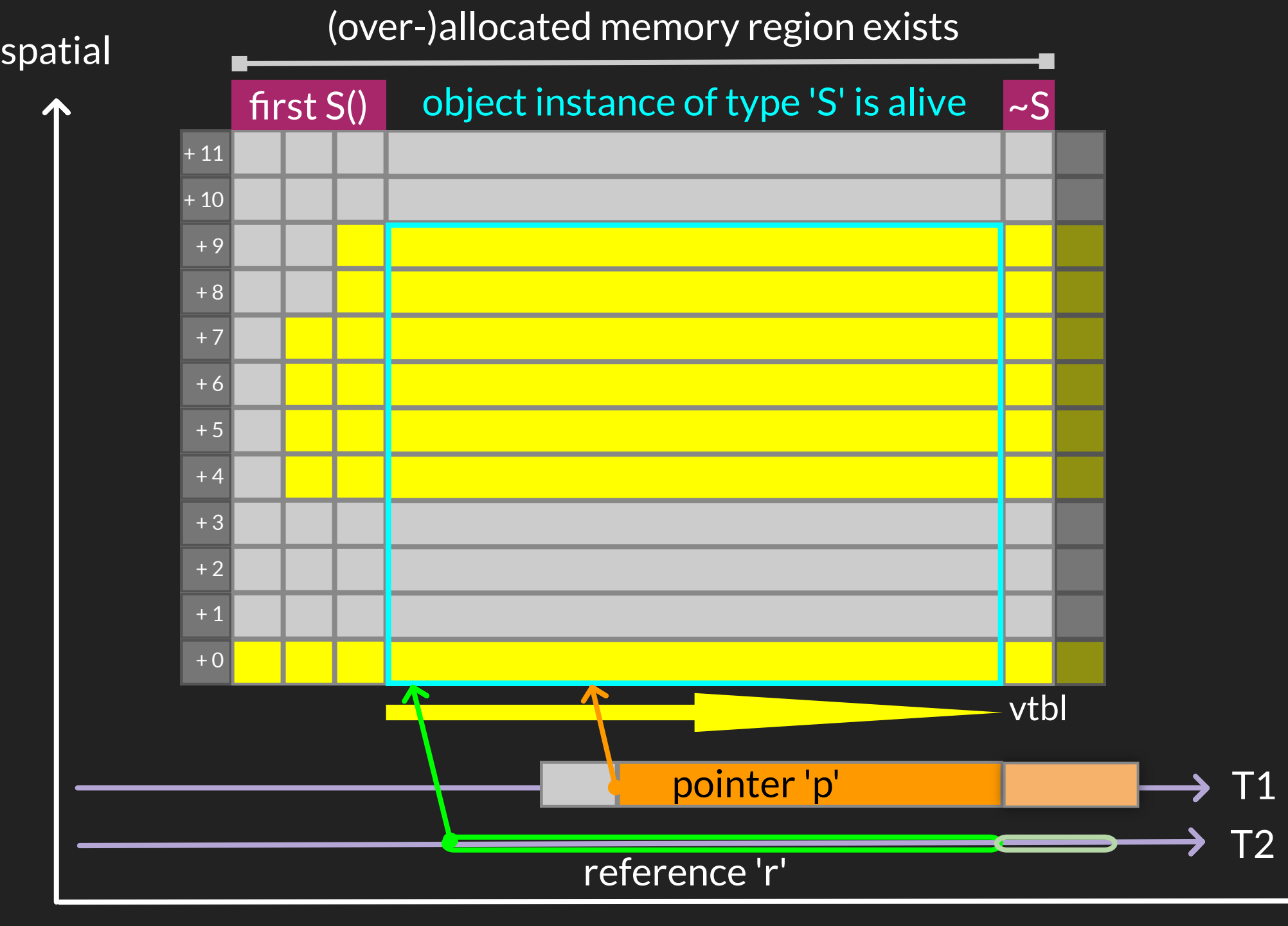


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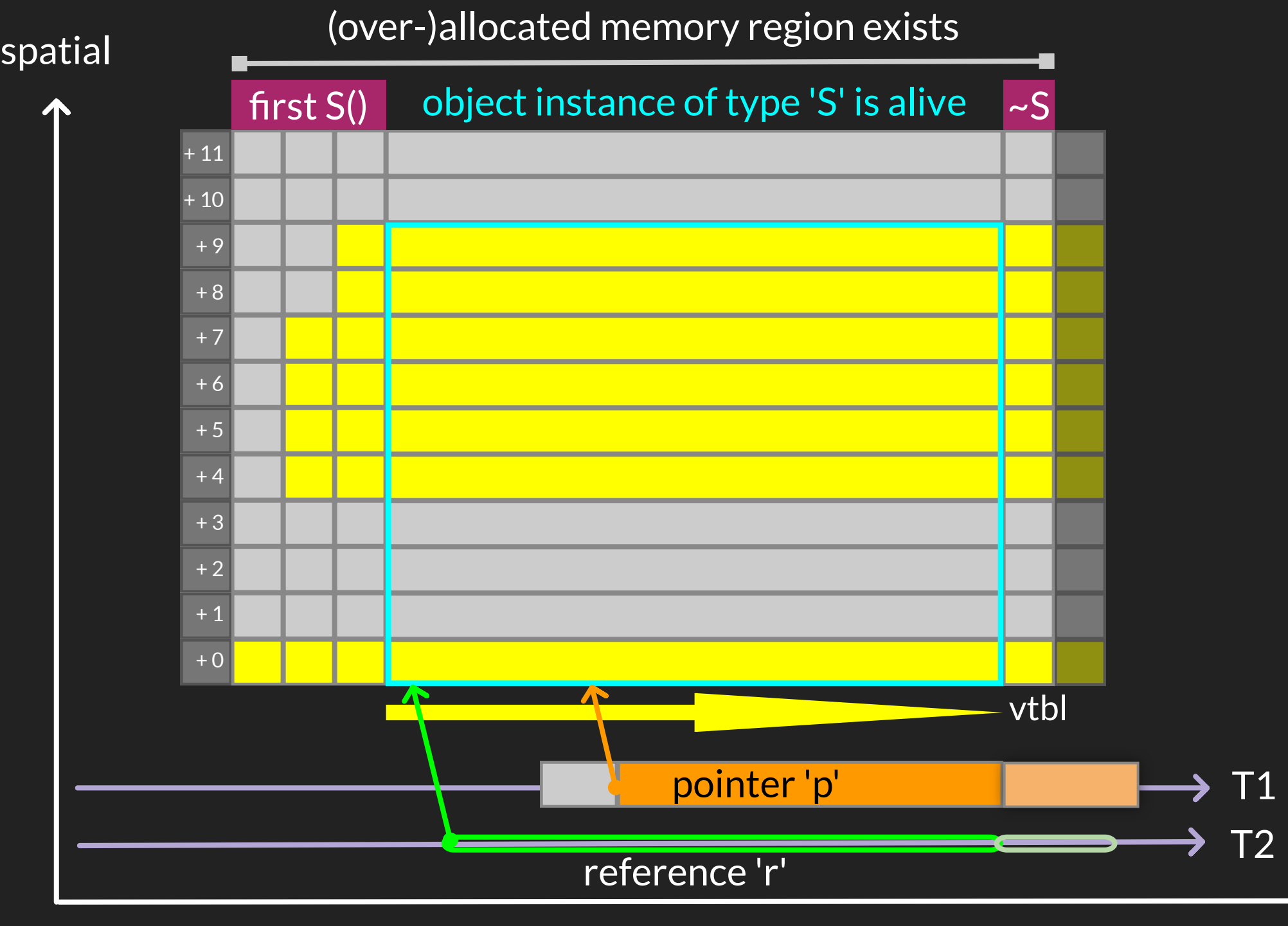


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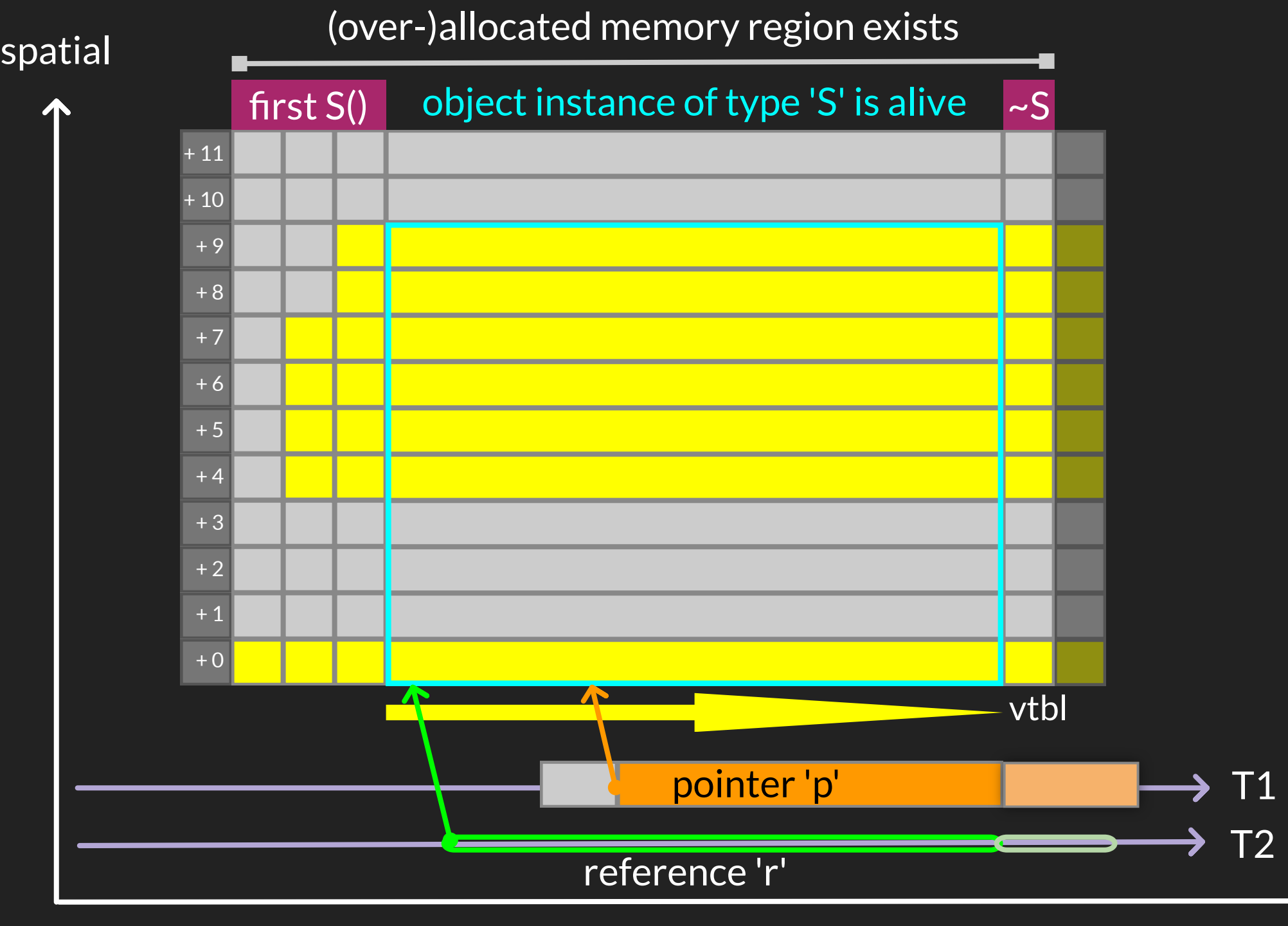


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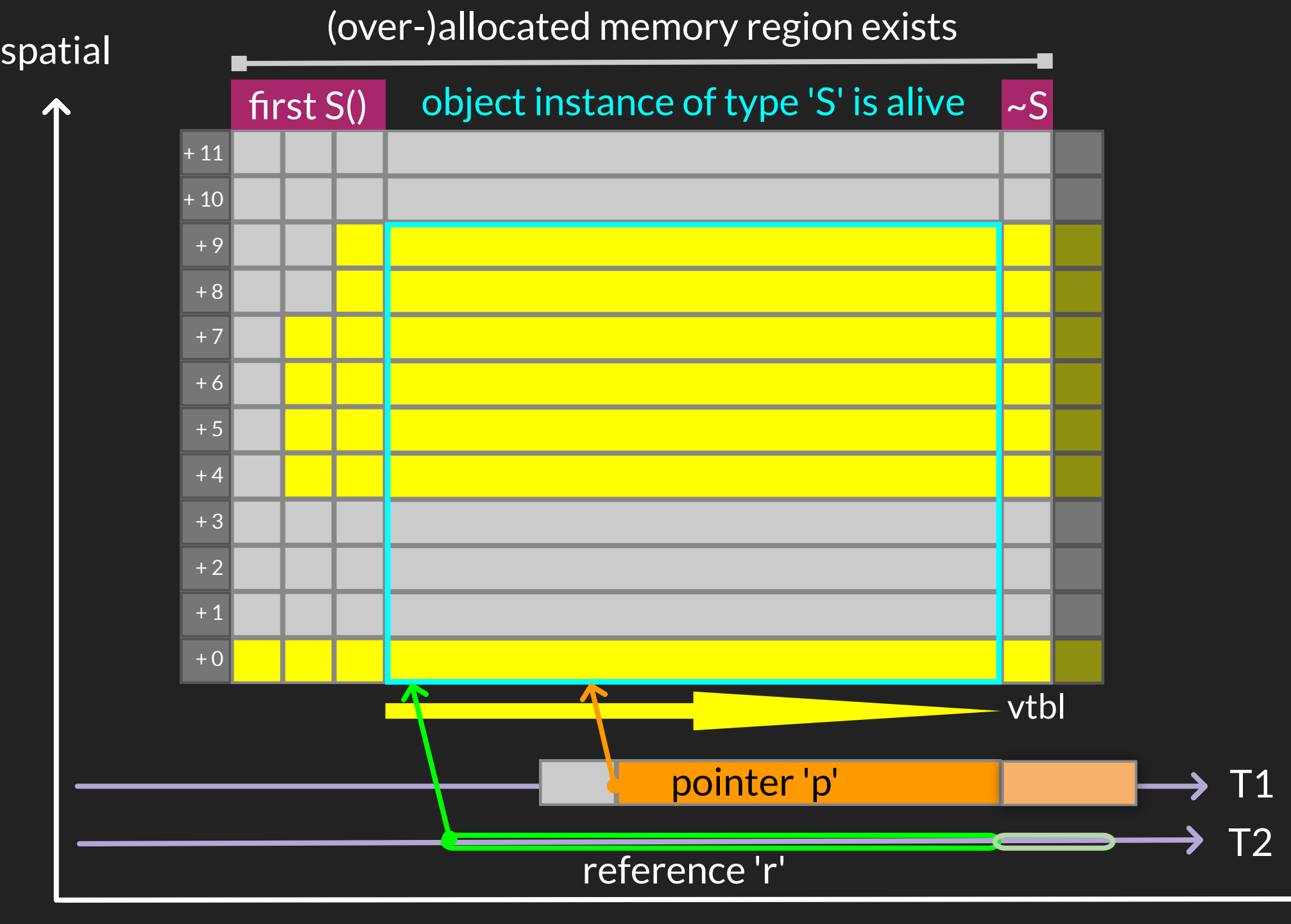


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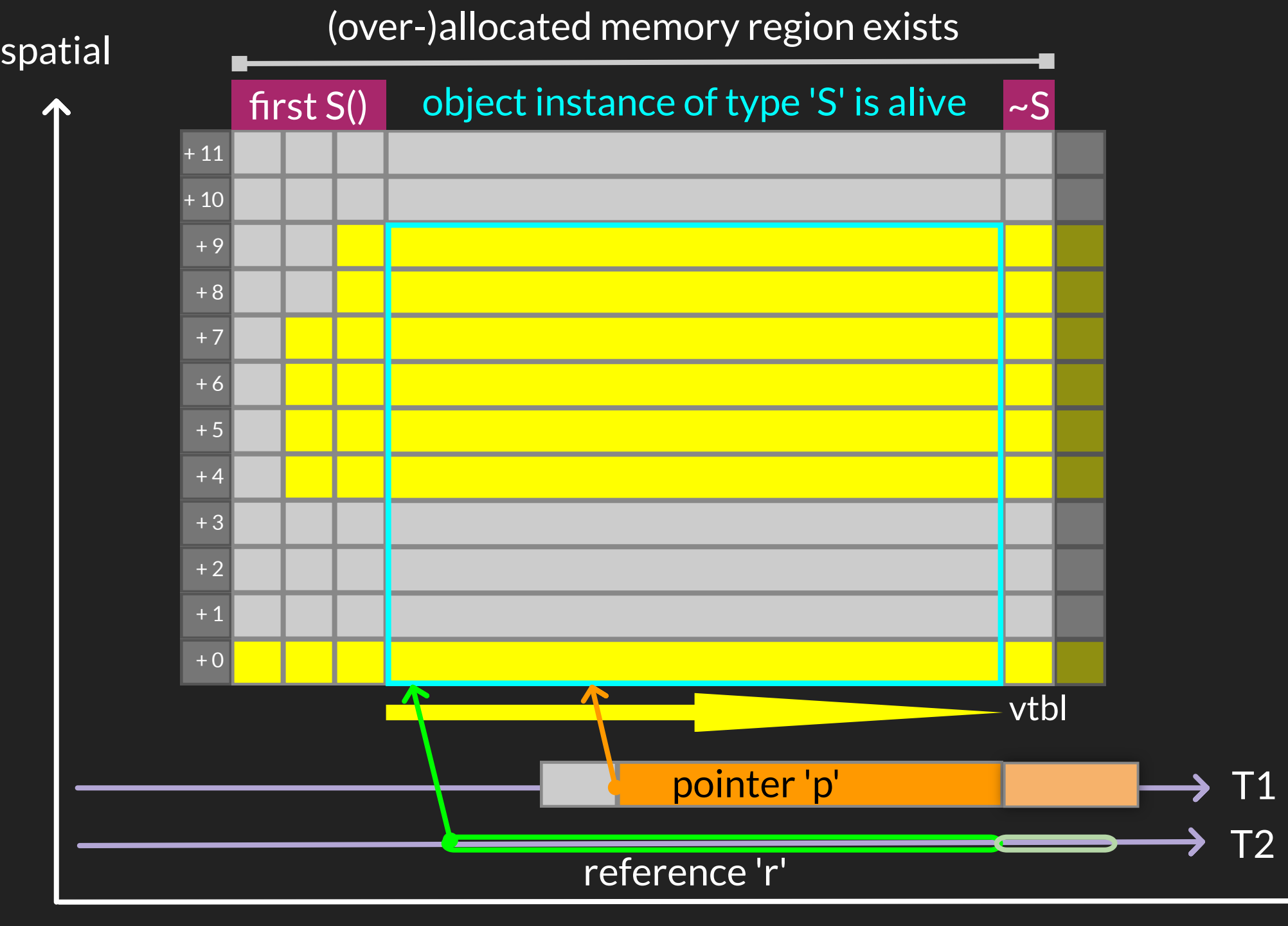


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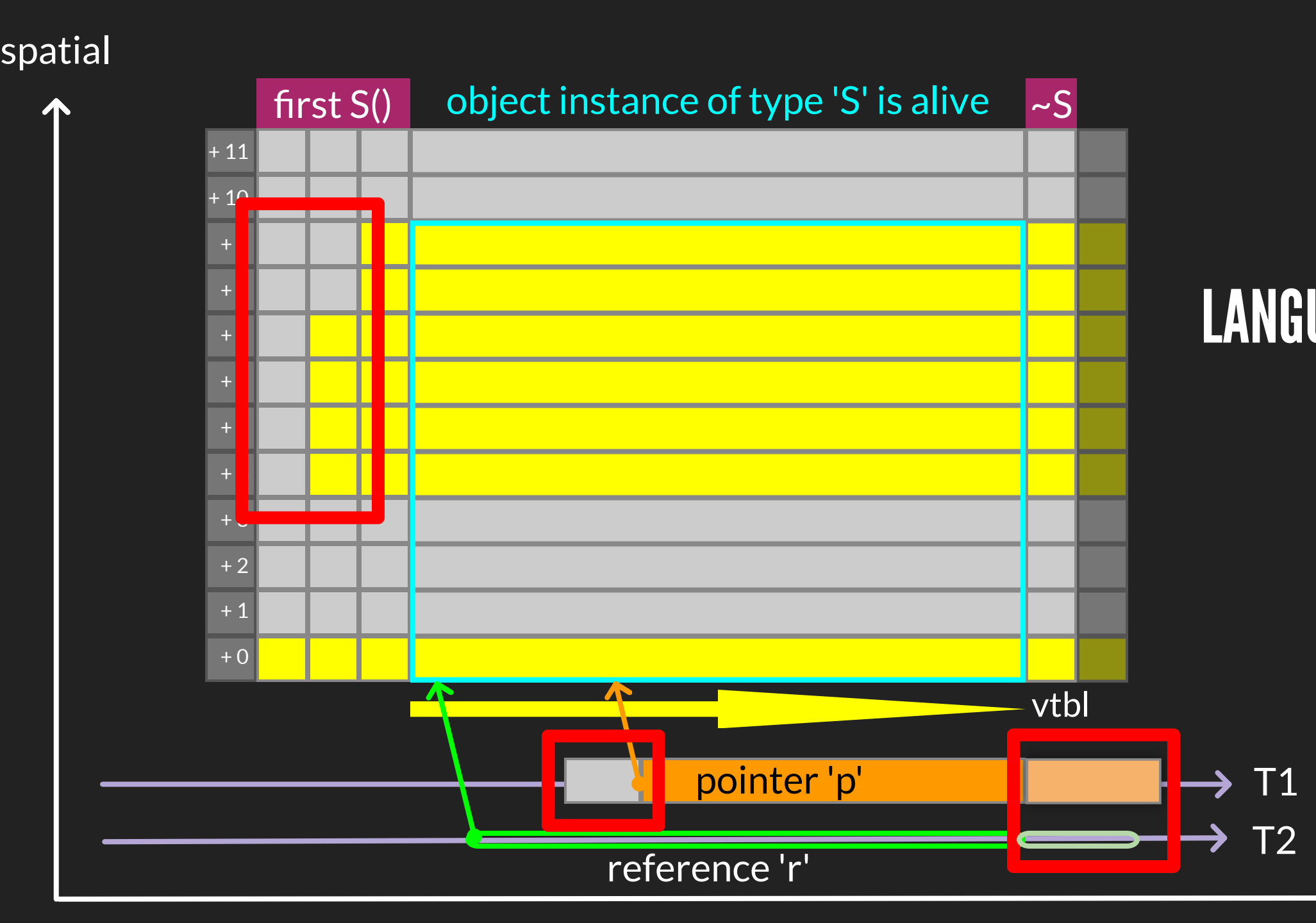
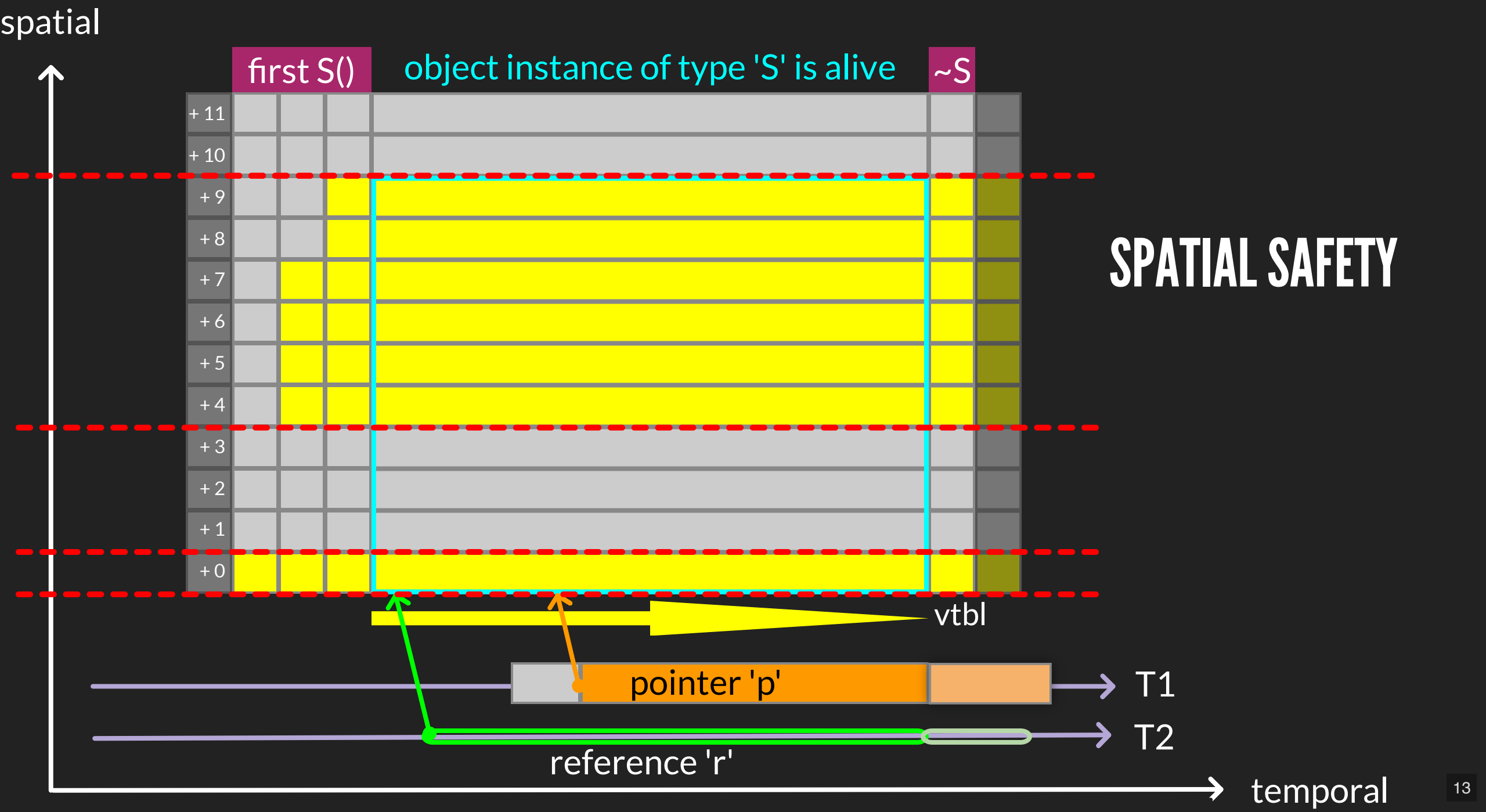
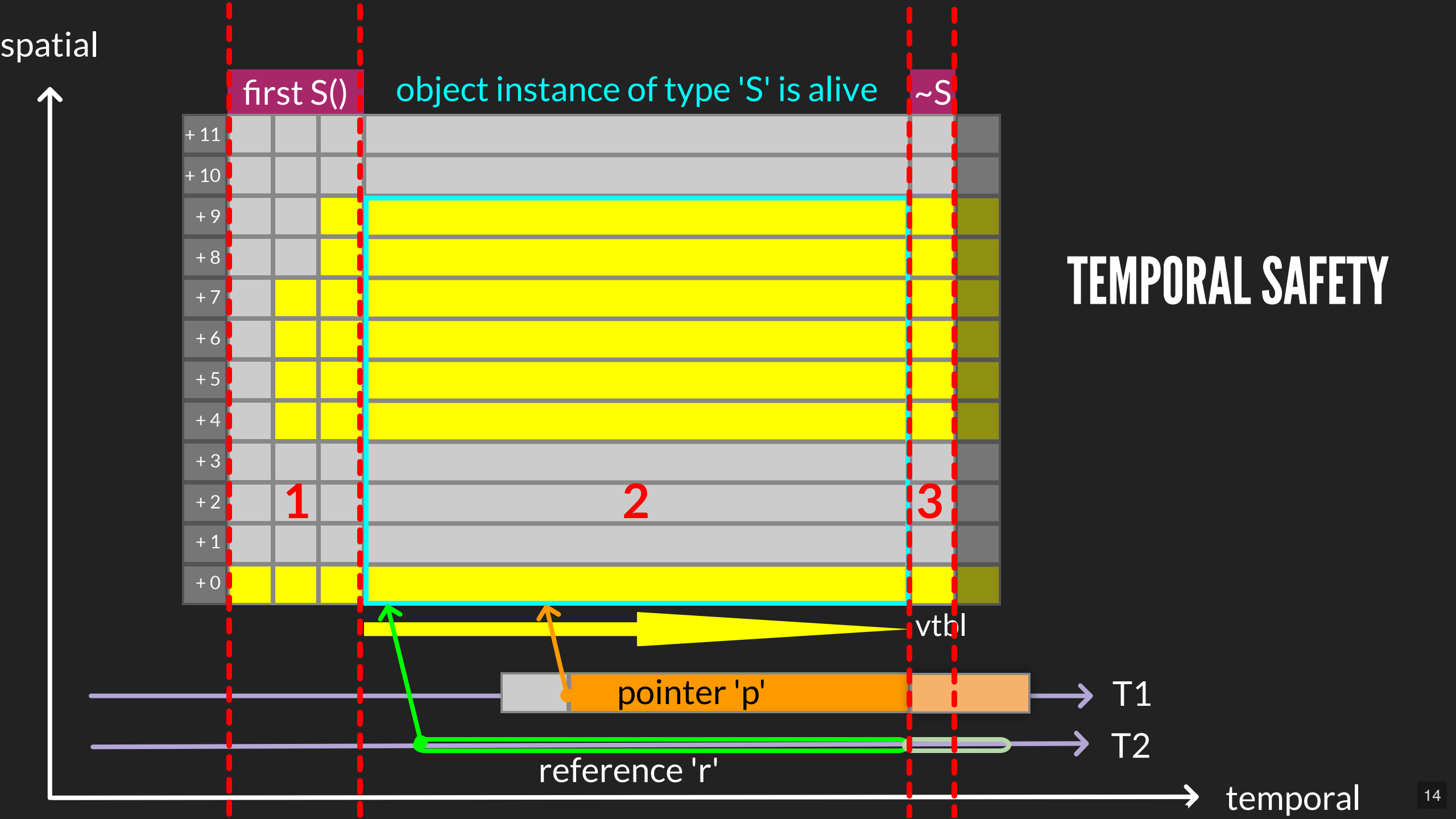


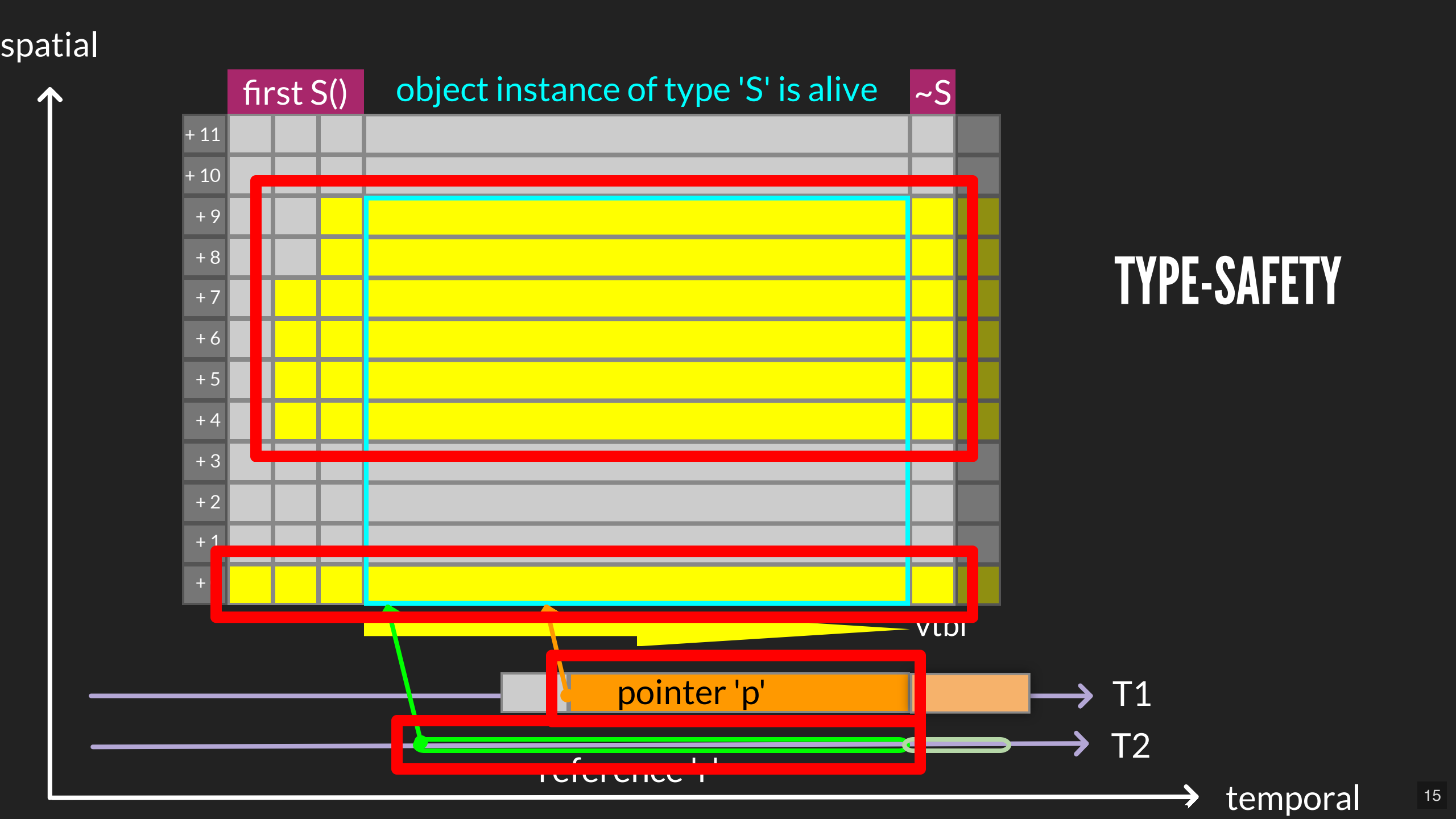
LANGUAGE-SAFETY



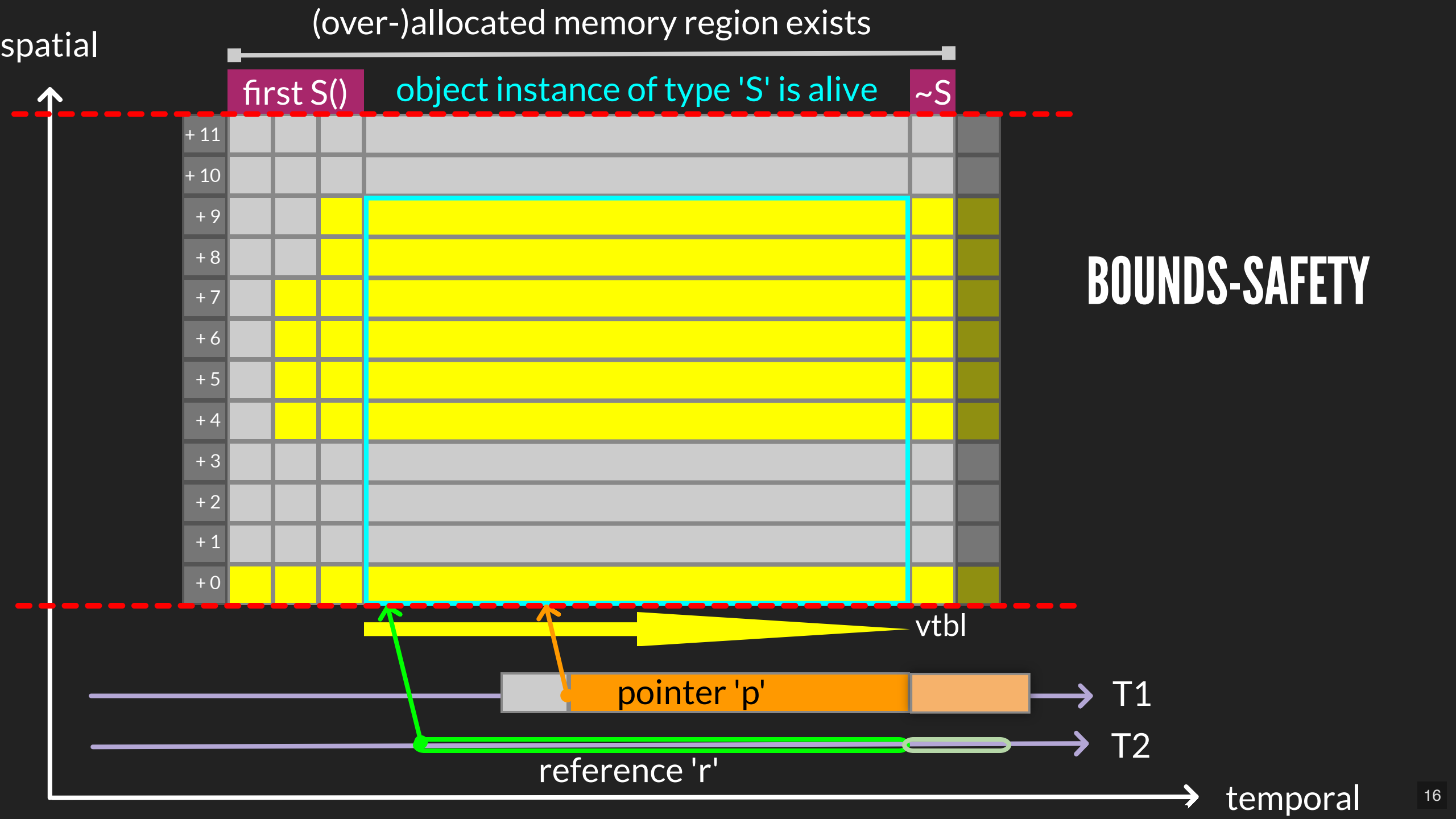
SPATIAL SAFETY



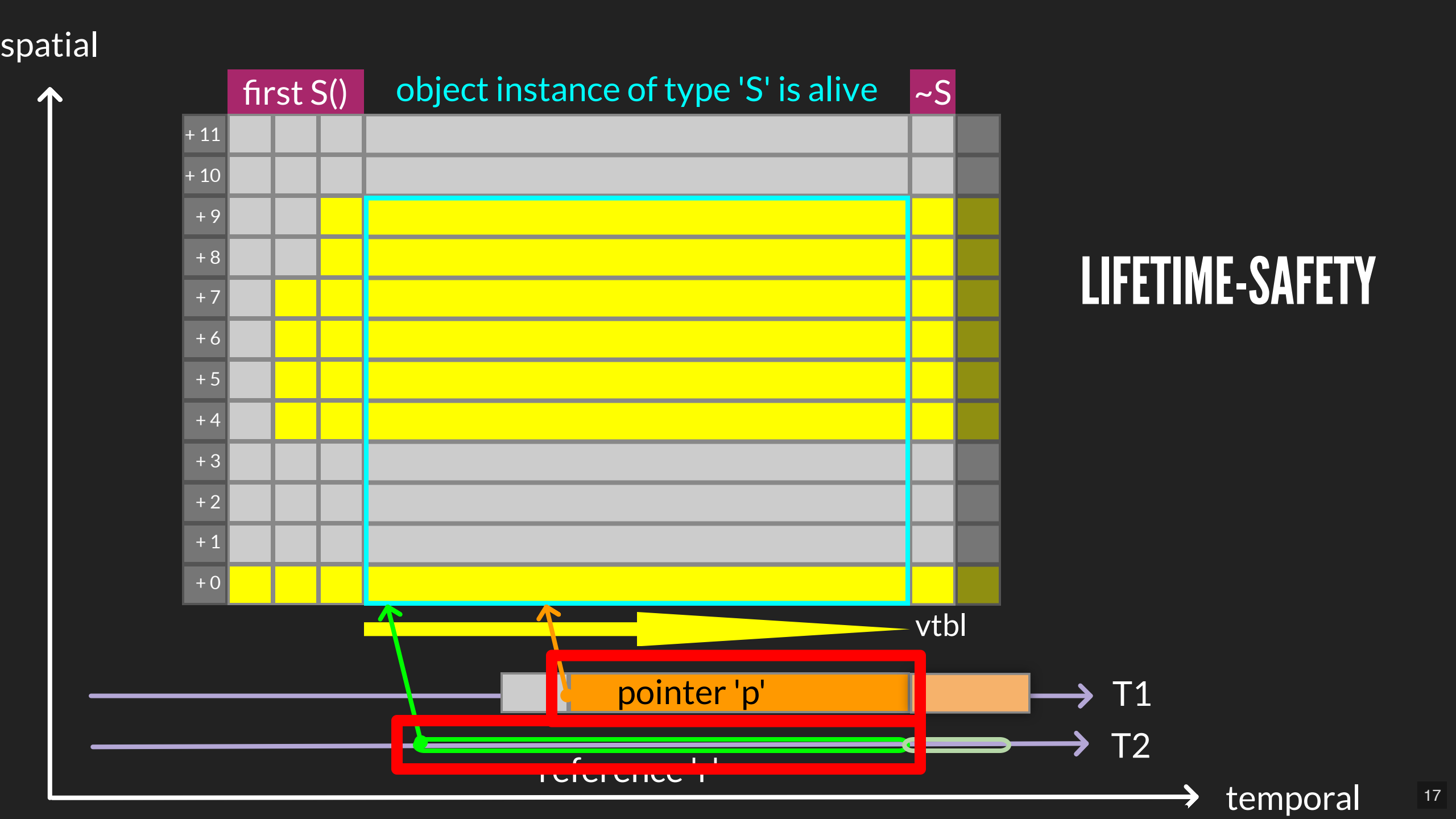
TEMPORAL SAFETY


spatial
first S()
object instance of type 'S' is alive
~S
+ 11
+ 10
+ 9
+ 8
+ 7
+ 6
+ 5
+ 4
+ 3
+ 2
+ 1
+
vtbl
pointer 'p'
T1
T2
temporal

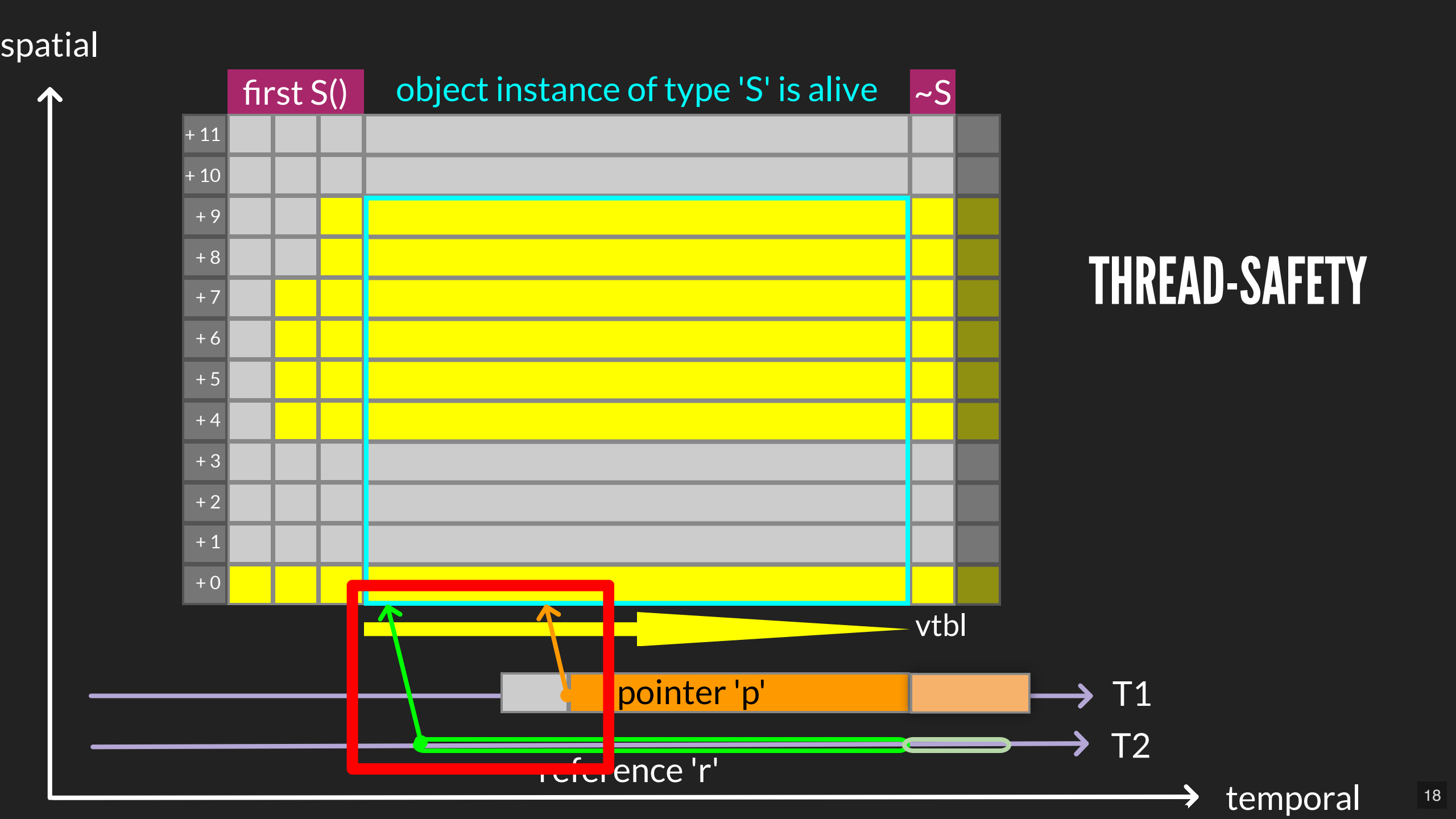
TYPE-SAFETY



BOUNDS-SAFETY



LIFETIME-SAFETY



THREAD-SAFETY

IN REAL LIFE ...


SECURITY


SECURITY


GMH Prüftechnik


FUNCTIONAL
SAFETY


FUNCTIONAL
SAFETY


BOTH


BOTH


GOING DOWN ...

```cpp
// contents of f.cpp

#include "f.h"

S s;
U u;

constexpr int f() {
    int *sp = s.b;
    int *sq = &s.b[0];
    int *sr = &s.b[4];
    int *st = &s.c;

    assert( sp ==  sq);
    assert( sr ==  st);
    assert(*sr == *st);

    int *up = u.b;
    int *uq = &u.b[0];
    int *ur = &u.b[4];
    int *ut = &u.c;

    assert( up ==  uq);
    assert( uq ==  ut);
    assert(*ur == *ut);

    return 0;
}

int main() {
    int rc = f();
    return rc;
}
```

```cpp
// contents of f.h

// product type

struct S {
    int a;
    int b[4];
    int c;
};

// sum type

union U {
    int a;
    int b[4];
    int c;
};
```

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    int *ut = &u.c;

    assert( up ==  uq);
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}

int main() {
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// product type

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    int a;
    int b[4];
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union U {
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    int *uq = &u.b[0];
    int *ur = &u.b[4];
    int *ut = &u.c;

    assert( up ==  uq);
    assert( uq ==  ut);
    assert(*ur == *ut);

    return 0;
}

int main() {
    int rc = f();
    return rc;
}
```

```cpp
// contents of f.h

// product type

struct S {
    int a;
    int b[4];
    int c;
};

// sum type

union U {
    int a;
    int b[4];
    int c;
};
```

https://godbolt.org/z/snPW3bYGE

```cpp
// contents of f.cpp

#include "f.h"

constexpr int f() {
    S s;              // uninitialized objects in
    U u;              // automatic or dynamic memory

    int *sp = s.b;
    int *sq = &s.b[0];
    int *sr = &s.b[4];
    int *st = &s.c;

    assert( sp ==  sq);
    assert( sr ==  st);
    assert(*sr == *st); // GCC complains about UB
     // erroneous behaviour (EB) 🚀 in C++26 💥🛡️
    int *up = u.b;
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int main() {
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};
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int main() {
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    int a;
    int b[4];
    int c;
};

// sum type

union U {
    int a;
    int b[4];
    int c;
};
```

```cpp
// contents of f.cpp

#include "f.h"

constexpr int f() {
    S s{};              // initialized, best practice
    U u{};              // {} available since C++11
                        // no more UB or EB 👍
    int *sp = s.b;
    int *sq = &s.b[0];
    int *sr = &s.b[4];
    int *st = &s.c;

    assert( sp ==  sq);
    assert( sr ==  st);
    assert(*sr == *st);

    int *up = u.b;
    int *uq = &u.b[0];
    int *ur = &u.b[4];
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    assert( up ==  uq);
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    return 0;
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int main() {
    int rc = f();
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}
```

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// contents of f.h

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struct S {
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    int a;
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};
```

```cpp
// contents of f.cpp

#include "f.h"

constexpr int f() {
    S s{};              // initialized
    U u{};              // no more EB

    int *sp = s.b;
    int *sq = &s.b[0];
    int *sr = &s.b[4];
    int *st = &s.c;

    assert( sp ==  sq);
    assert( sr ==  st);
    assert(*sr == *st);

    int *up = u.b;
    int *uq = &u.b[0];
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    assert( up ==  uq);
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int main() {
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struct S {
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https://godbolt.org/z/qqsfExKdr

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    int *sp = s.b;
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    int a;
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    int *sp = s.b;
    int *sq = &s.b[0];
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    int *st = &s.c;

    assert( sp ==  sq);
    assert( sr ==  st);
    assert(*sr == *st); // UB: out of bounds read

    int *up = u.b;
    int *uq = &u.b[0];
    int *ur = &u.b[4];
    int *ut = &u.c;

    assert( up ==  uq);
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    int *up = u.b;
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    int *ut = &u.c;

    assert( up ==  uq);
    assert( uq ==  ut);
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                        // UB: inactive member
    return 0;
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int main() {
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    int *sp = s.b;
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    assert( sp ==  sq);
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// contents of f.cpp

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    int *sp = s.b;
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struct S {
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// sum type

union U {
    int a;
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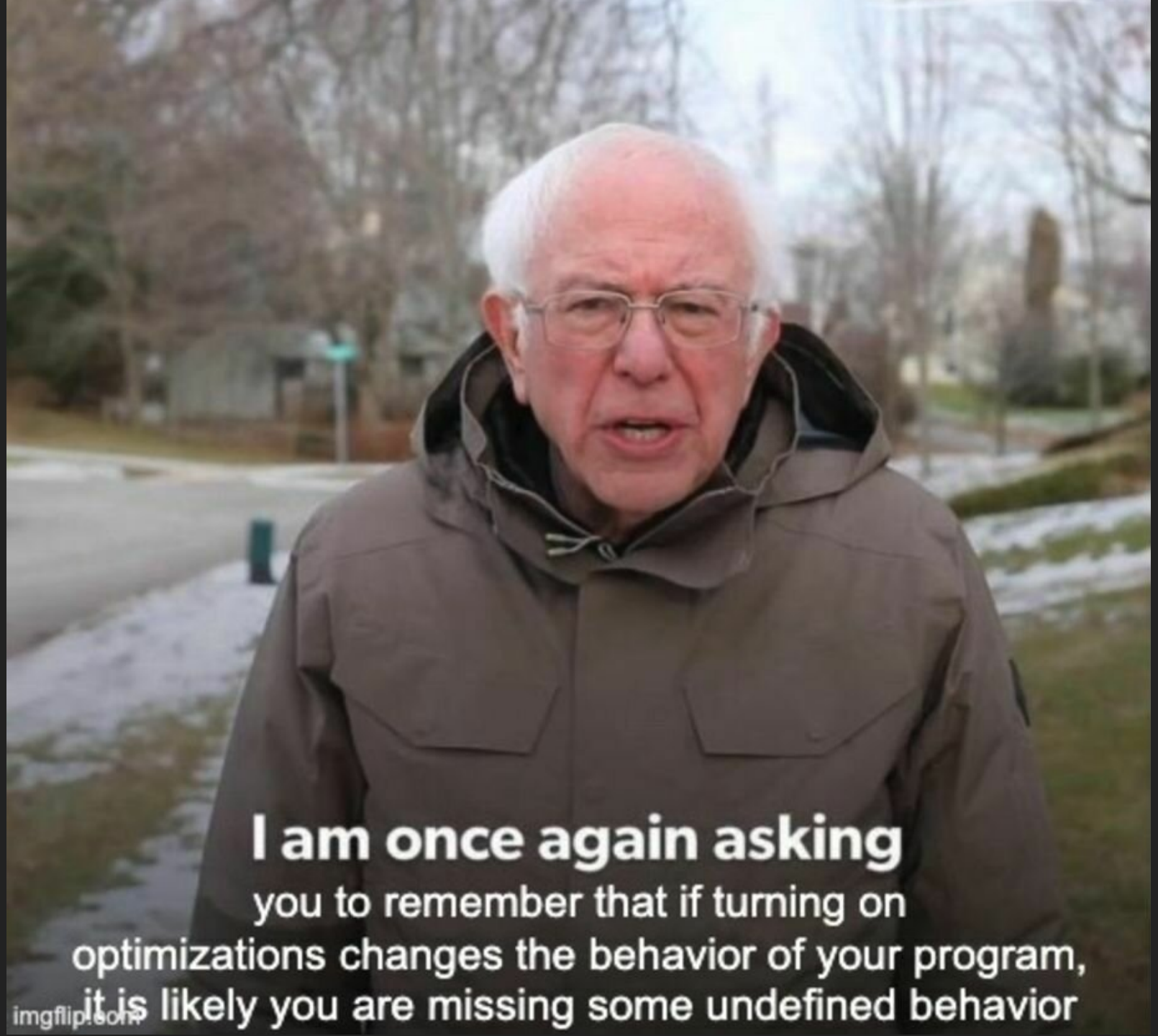
};
```

The current C++ standard document mentions "undefined behaviour" (UB) ca. 140 times in the language-specific part.


This is fine.


I am once again asking
you to remember that if turning on
optimizations changes the behavior of your program,
it is likely you are missing some undefined behavior
imgflip.com

Constant evaluation

Constant evaluation
is mandated to
refuse and diagnose all occurences of UB
during program execution.

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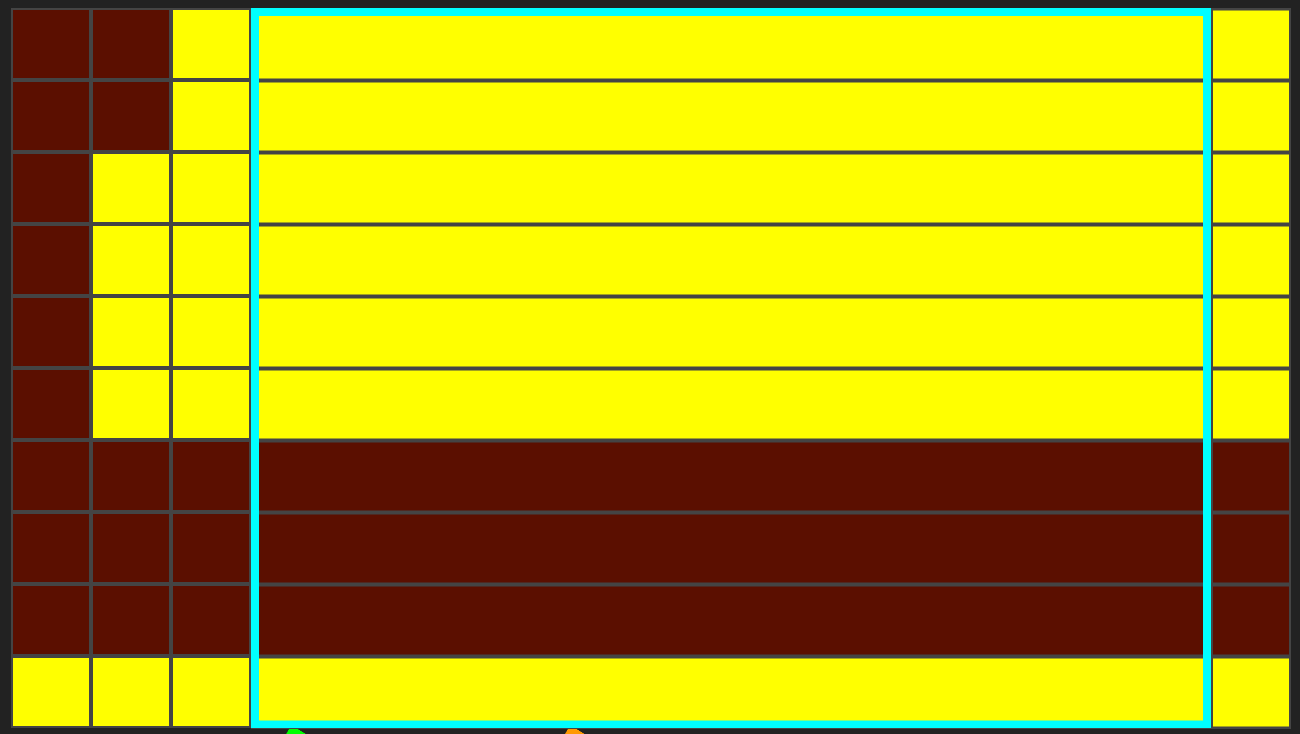
[defns.undefined], [expr.const]/10

spatial

first S()

object instance of type 'S' is alive

~S



pointer 'p'

F1

F2

reference 'r'

temporal

```
struct S {
  S();
  virtual ~S();

  char    a = 1;
  int32_t b = 2;
  int16_t c = 3;
};

constexpr
void Function1 {
  S _;
  S * p = &_;
}

constexpr
void Function2 {
  S _;
  S & r = _;
}
```

```
1  constexpr int f(const int *array, bool a, bool b) {
2      unsigned index = 1;
3
4      if (a) --index;
5      if (b) --index;
6
7      return array[index];
8  }
9
10 constexpr int array[4]{};
11
12 static_assert(f(array, false, false) == 0);
13 static_assert(f(array, true,  false) == 0);
14 static_assert(f(array, false, true ) == 0);
15
16 int main() {
17     return
18         (f(array, false, false) == 0)
19       + (f(array, true,  false) == 0)
20       + (f(array, false, true ) == 0);
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```

100% code coverage! 

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13 static_assert(f(array, true,  false) == 0);
14 static_assert(f(array, false, true ) == 0);
15 static_assert(f(array, true,  true ) == 0); // fails!
16
17 int main() {
18     return
19         (f(array, false, false) == 0)
20       + (f(array, true,  false) == 0)
21       + (f(array, false, true ) == 0)
22       + (f(array, true,  true ) == 0);      // UB!
23 }
```

```cpp
constexpr int f(const int *array, bool a, bool b) {
    unsigned index = 1;

    if (a) --index;
    if (b) --index;

    return array[index];
}

constexpr int array[4]{};

static_assert(f(array, false, false) == 0);
static_assert(f(array, true,  false) == 0);
static_assert(f(array, false, true ) == 0);
static_assert(f(array, true,  true ) == 0); // fails!

int main() {
    return
        (f(array, false, false) == 0)
      + (f(array, true,  false) == 0)
      + (f(array, false, true ) == 0)
      + (f(array, true,  true ) == 0);      // UB!
}
```

100% path coverage!

CONSTEXPR

- since C++11
- major improvements until C++20
- minor language improvements in C++23, but huge library improvements

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- since C++11
- major improvements until C++20
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new in C++26:

- coroutines
- exceptions
- placement new
- structured bindings
- improved references
- lots more library functions


MORE CODE ...

```
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6
7      return array[index];
8  }
9
10 constexpr int array[4]{};
11
12 static_assert(f(array, false, false) == 0);
```
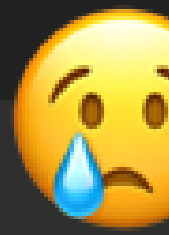
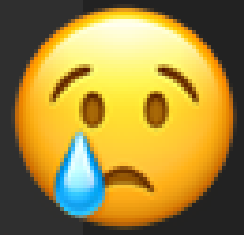

```
1  constexpr int f(const int *array, bool a, bool b) {
2      unsigned index = 1;
3
4      if (a) --index;
5      if (b) --index;
6
7      // implicit contract: index lies within the referenced array
8      return array[index];
9  }
10
11 constexpr int array[4]{};
12
13 static_assert(f(array, false, false) == 0);
```



```
1  constexpr int f(const int (&array)[4], bool a, bool b) {
2      unsigned index = 1;
3
4      if (a) --index;
5      if (b) --index;
6
7      // perform a range check here!
8      return array[index];
9  }
10
11 constexpr int array[4]{};
12
13 static_assert(f(array, false, false) == 0);
```

```cpp
template <std::size_t N>
constexpr int f(const int (&array)[N], bool a, bool b) {
    unsigned index = 1;

    if (a) --index;
    if (b) --index;

    // perform a range check here!!
    return array[index];
}

constexpr int array[4]{};

static_assert(f(array, false, false) == 0);
```

```
1  constexpr int f(const int array[], std::size_t N, bool a, bool b) {
2      unsigned index = 1;
3
4      if (a) --index;
5      if (b) --index;
6
7      // perform a range check here!!!!
8      return array[index];
9  }
10
11 constexpr int array[4]{};
12
13 static_assert(f(array, std::size(array), false, false) == 0);
```



```cpp
#include <span>  // "Contemporary C++"

constexpr int select(std::span<const int> sequence,
                     SomeBoolFeature a, OtherBoolFeature b) {
    unsigned index = 1;

    if (a) --index;
    if (b) --index;

    // ¡ perform a range check here !
    return sequence[index];
}

constexpr int array[4]{};

static_assert(select(array, option_a, feature_b) == 0);
```

```cpp
#include <span>  // "Contemporary C++"

constexpr int select(std::span<const int> sequence,
                     SomeBoolFeature a, OtherBoolFeature b) {
    unsigned index = 1;

    if (a) --index;
    if (b) --index;

    // ¡ perform a range check here !
    return sequence[index];
}

constexpr int array[4]{};

static_assert(select(array, option_a, feature_b) == 0);
```

```cpp
#include <span>

constexpr int select(std::span<const int> sequence,
                     SomeBoolFeature a, OtherBoolFeature b) {
    unsigned index = 1;

    if (a) --index;
    if (b) --index;

    // range checking is internally done
    // in a 'hardened' standard library!
    return sequence[index];
}

constexpr int array[4]{};

static_assert(select(array, option_a, feature_b) == 0);
```

P3471

Standard library hardening

P3471

Standard library hardening

Expect this before C++26 !

Louis Dionne "Security in C++", C++Now 2024

C++ library preconditions

- are either checked with termination semantics in all compilation modes,
- or are ignored → UB (status quo)

- detected contract violations
  - may stop execution instantly (without P2900)
  - detour to handle_contract_violation (with P2900)

C++ library preconditions

- are either checked with termination semantics in all compilation modes,
- or are ignored → UB (status quo)

- detected contract violations
  - may stop execution instantly (without P2900)

  - detour to handle_contract_violation (with P2900)

C++ standard libraries may go beyond P3471

- more containers
- more classes
- more functions

- destructor pointer tombstones → resist "use after free" 😎

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- more classes
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Available in MS-STL, libc++, ... !

```cpp
import std;

int main() {
    std::println("hardened STL: {}", static_cast<bool>(_MSVC_STL_HARDENING));

    std::vector v = { 1, 2, 3 };
    std::println("v[3]  = {}", v[3]);
    std::println("v[-1] = {}", v[-1]);
}
```

MS-STL version 202502

just as ever

with hardening

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MS-STL version 202502

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> cl test.cpp
> test.exe
hardened STL: false
v[3]  = 9673
v[-1] = -1811929271

// program ended with return value 0
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// program ended with return value 0
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with hardening

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> cl test.cpp
> test.exe
hardened STL: true

// program execution stopped here
// with error code 0xC0000409
// i.e. STATUS_FAIL_FAST_EXCEPTION
```

DILIGENCE

P2900

Contracts for C++

P2900

Contracts for C++

Similar to Eiffel, Ada, or D

CONTRACTS IN C++

Support Developers

CONTRACTS IN C++

Assist "Design by Contract"

CONTRACTS IN C++

Check Correctness

```
1  // anywhere
2
3  int func(int x)
4  // precondition:  x is not 1
5  // postcondition: result value is different from argument value
6  {
7  // ...
8      assert(x != 3);  // assures an expectation
9  // ...
10     return x | 2;
11 }
12
13 void call_func() {
14     func(0);    // fine
15     func(1);    // oops
16     func(2);    // oh my...
17     func(3);    // what now?
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    // observable checkpoint (P1495 💥🛡) right before evaluating the assert-argument
    contract_assert(x != 3);   // an assertion statement, e.g. check invariants
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void call_func() {
    func(0);    // no contract violation
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    func(4);    // no contract violation
}

// ------------------------------------------------------------------------------

// in global namespace, global module, user-invisible

// called on any contract violation
// system-provided or optionally user-replaceable

void handle_contract_violation(std::contracts::contract_violation cvo) {
    // handle contract violation according to
    //   -  the evaluation semantics as indicated in 'cvo'
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CONTRACT EVALUATION SEMANTICS

Semantics	check condition	fail → invoke handler	terminate
ignore (zero overhead)	❌	❌	❌
observe	✅	✅ [1]	❌
enforce	✅	✅	✅ [2]
quick_enforce	✅	❌	✅ [3]

[1] compile-time: diagnostic

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[3] runtime: terminate abstract machine execution (i.e. no more user code)
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SAFE C++ ?

P3081

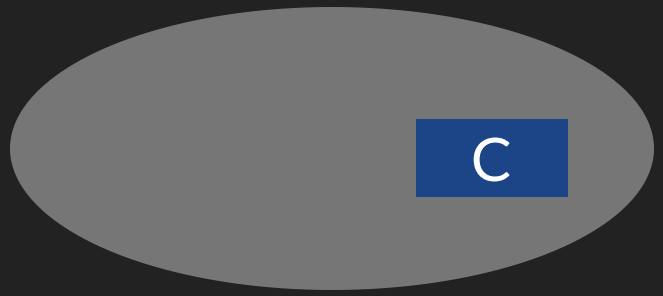
Core safety profiles for C++26

P3081

Core safety profiles for C++26

Not in C++26 ! 😬

THE IDEA



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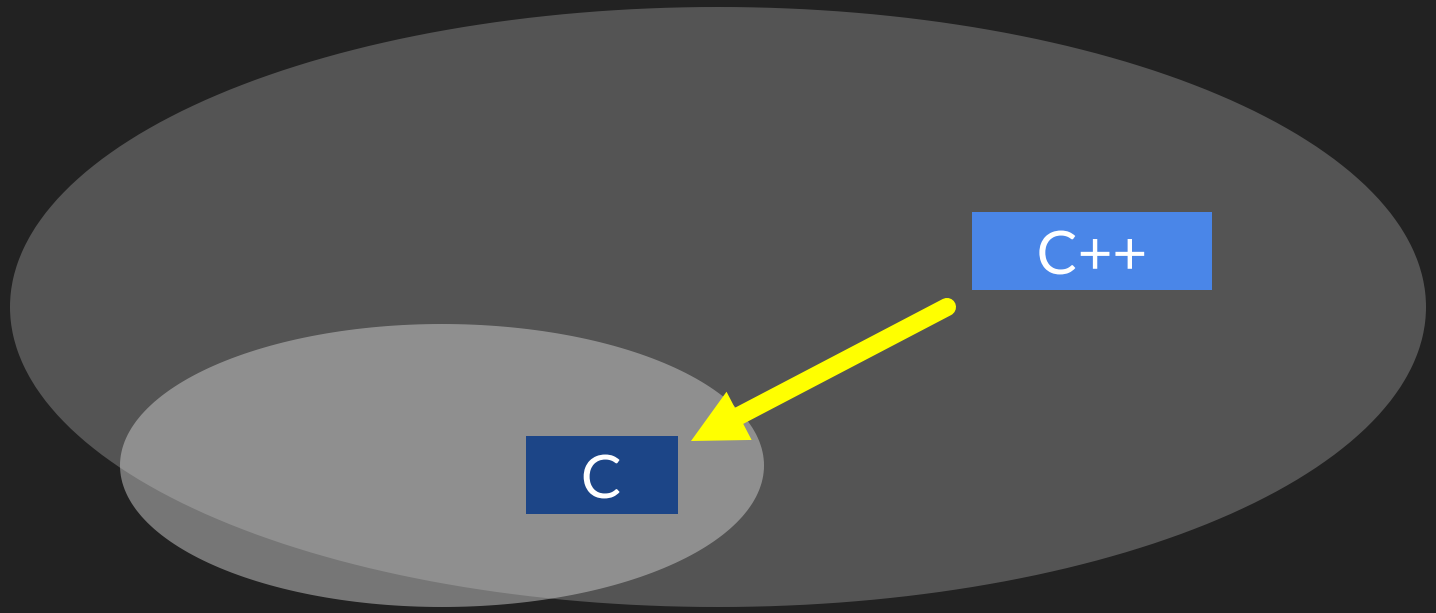

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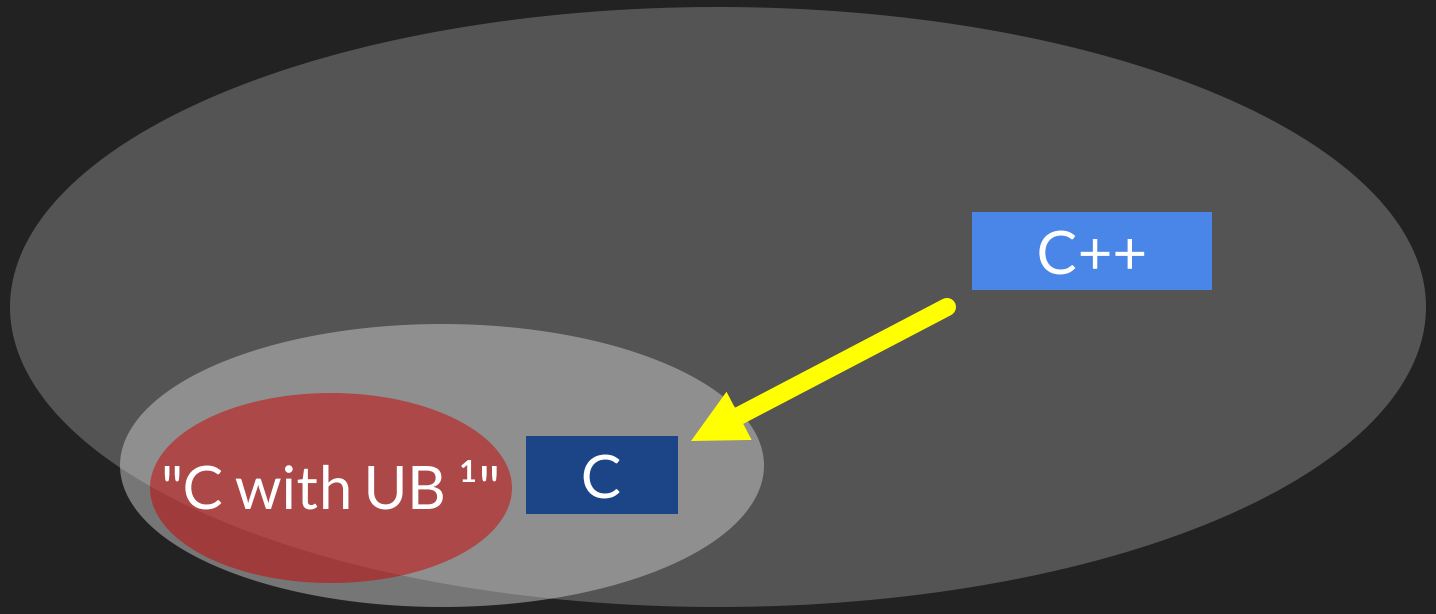

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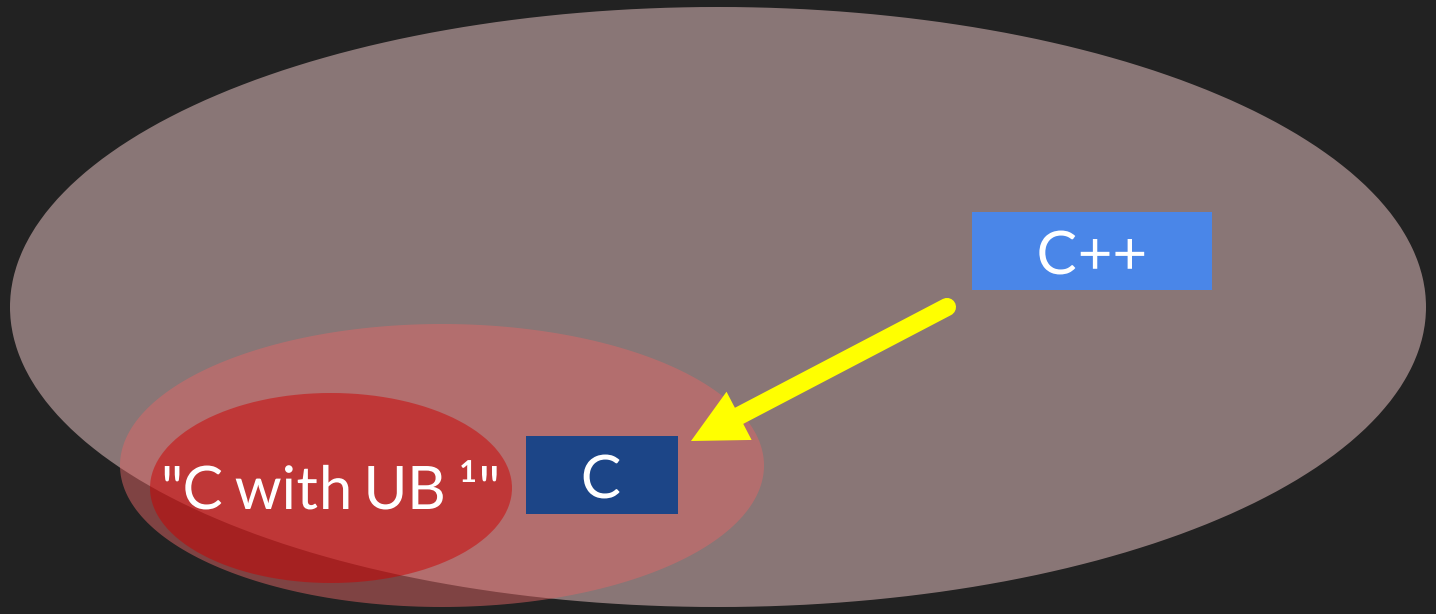

[1] WG14 N3453: C contains

- 100 cases of UB in the core language
- 221 cases of UB in total

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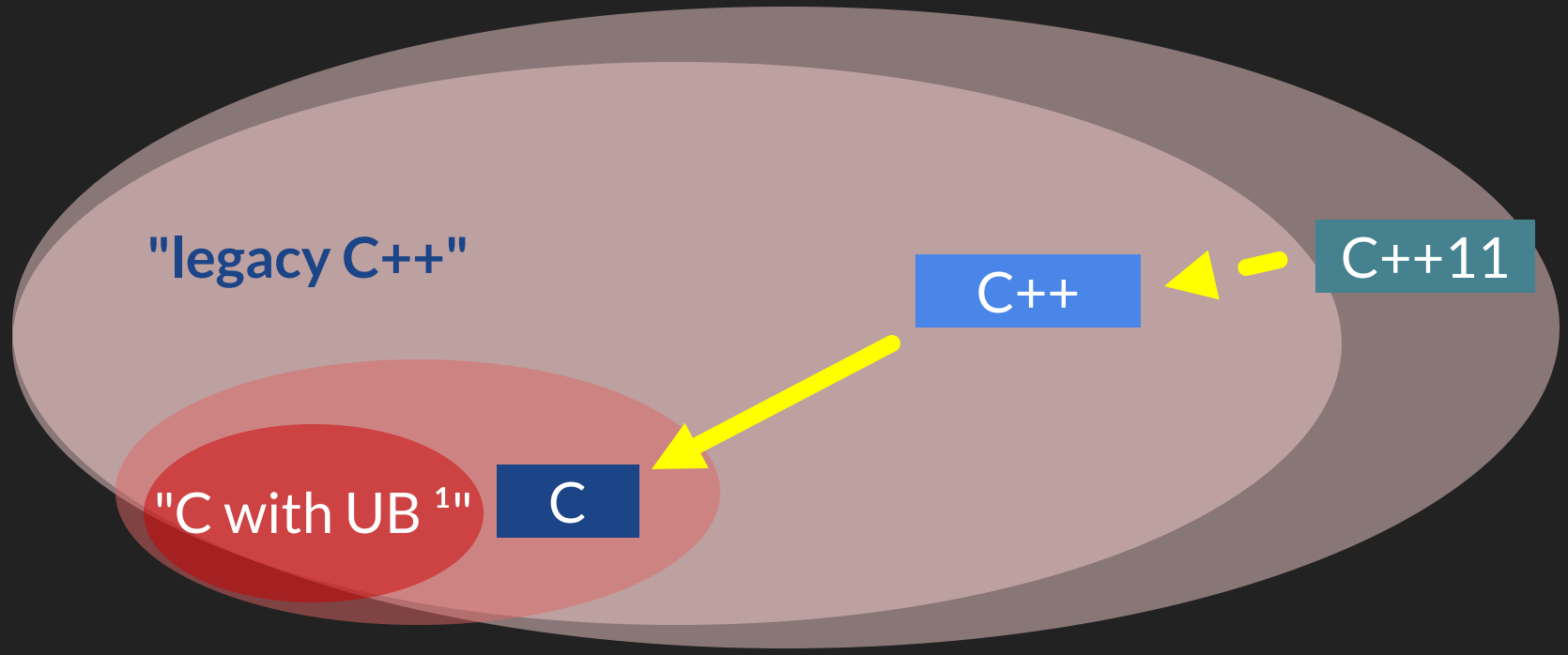

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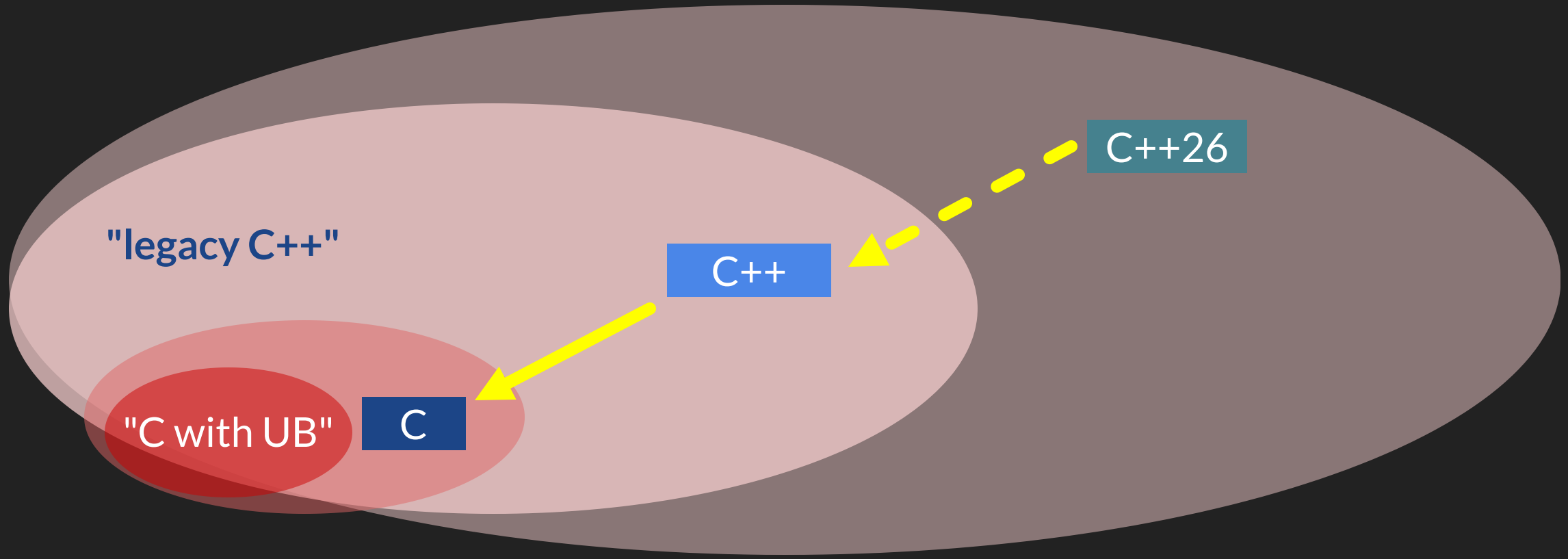

Inherited UB taints the entire language

C++ adds its own UB

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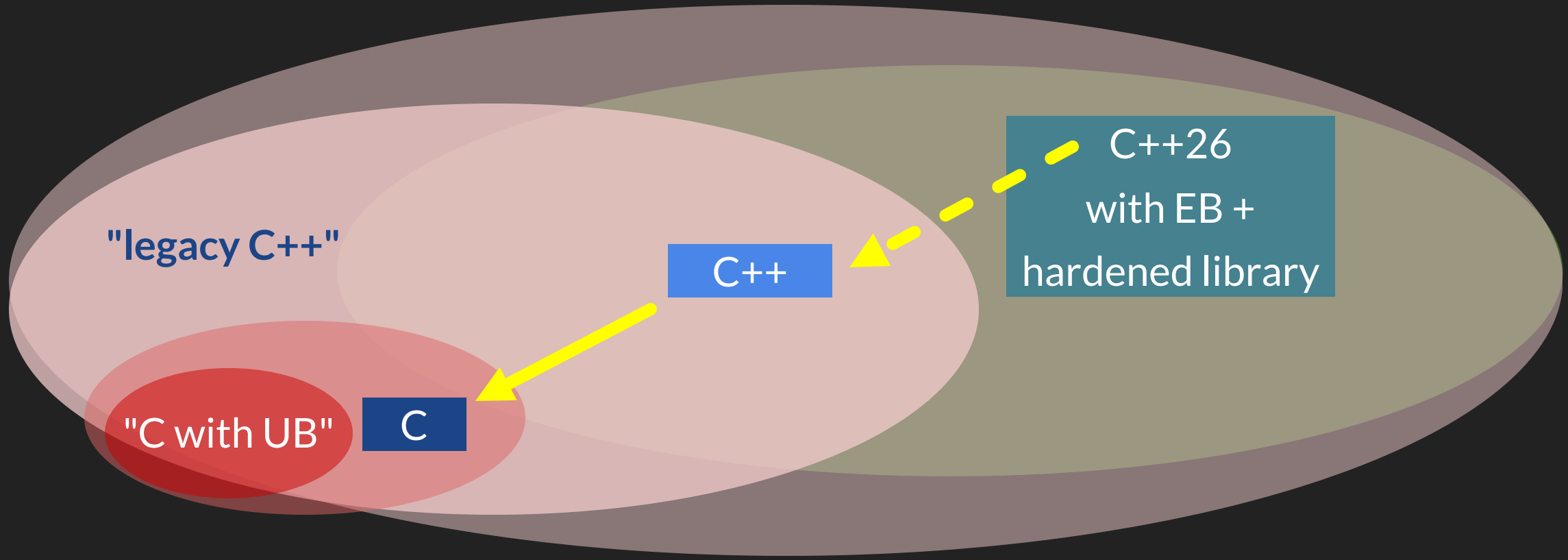

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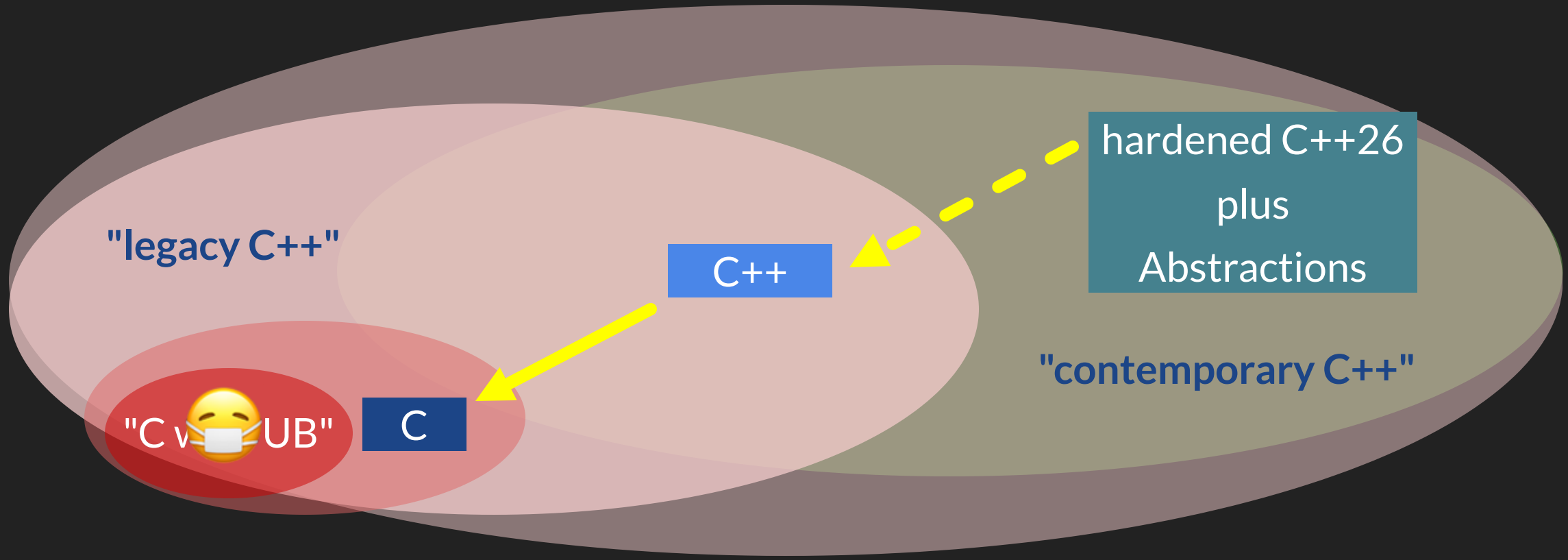

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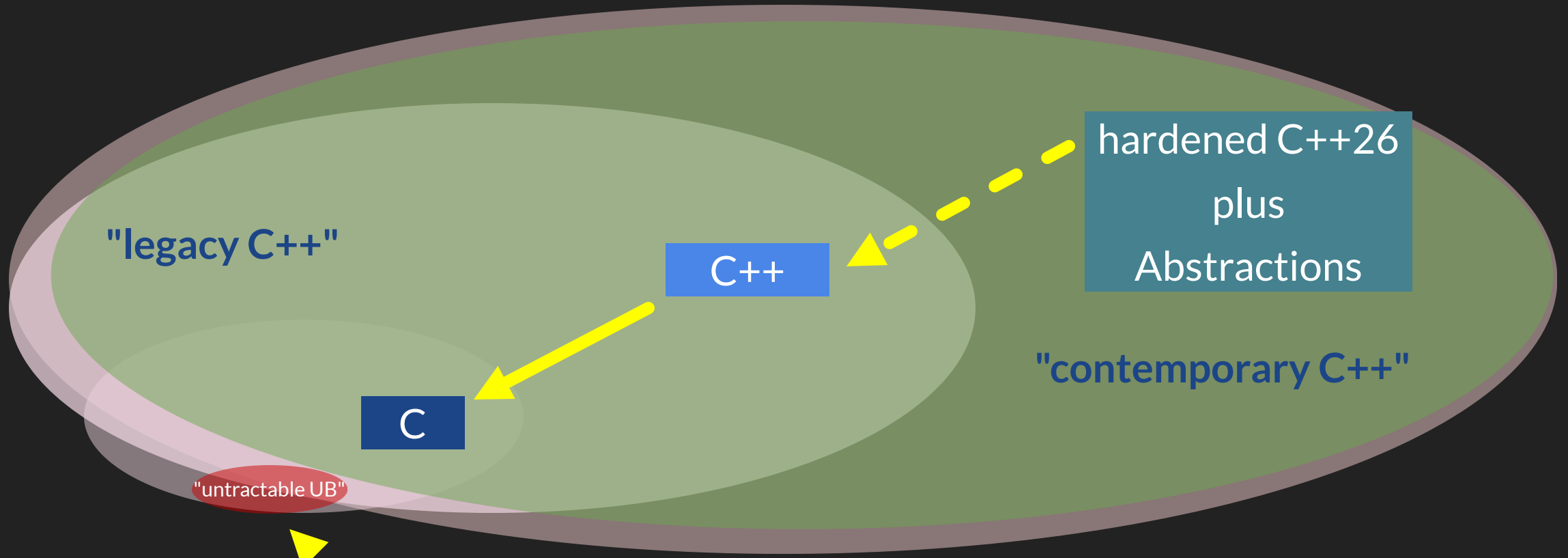


```
[[profiles::enforce(std::type)]];
[[profiles::enforce(std::bounds)]];
[[profiles::enforce(...)]];
```


BEYOND C++26

Tackle lifetime-safety?

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- life-time tracking and annotations like Rust (P3390 Safe C++)
  - might require major compiler efforts
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- pursue a third way
  - currently in development

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  - shift object across thread boundaries
  - will require cutting cross-thread references
  - might require dataflow analysis

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  - shift object across thread boundaries
  - will require cutting cross-thread references
  - might require dataflow analysis
- pursue non-trivial relocation?
  - will require dataflow analysis

Tackle all undefined behaviour?

Will be pursued in a Whitepaper along with EB, Contracts, Profiles

SUMMARY

- why this perceived push towards security?
- clarifications on terminology
- security versus functional safety
- implications of UB at runtime and compile-time
- compile-time testing
- hardening the C++ standard library
- C++ contracts
- C++ profiles
- path into the future

"Simplicity is prerequisite for reliability"

Edsger W. Dijkstra

RESOURCES

- Living, up-to-date C++ standard (currently at C++26 est.)
- The Case for Memory Safe Roadmaps
- P2900 Contracts for C++
- P3081 Core safety profiles for C++26
- P3589 C++ Profiles: The Framework

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Images: courtesy of Matúš Chochlík

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Ceterum censeo ABI esse frangendam