Understanding C++ value categories

C++ Day 2020 - online edition

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What’s ahead?

- What are value categories?

  (questions)

- Value categories in the wild

  (questions)

A little bit about me

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Quiz

```
struct Number {
  int value_ = {};
};

class T {
public:
  T(const Number &n) : n_{n} {}

  T(const T &) { puts("Copy c'tor"); }

  Number get() { return n_; }

private:
  Number n_;
};
```

```
static T create(Number &&n) {
  return T{std::move(n)};
}

int main() {
  T x = T{create(Number{42})};

  return x.get().value_;
}
```

What's the output?

What are value categories?

It all starts with...

...expressions!

*Value categories are **not about objects or class types**, they are about **expressions**!*

I mean, seriously...

…expressions!

What is an expression?

An expression is a sequence of operators and their operands, that specifies a computation.

Expression outcome

Expression evaluation may produce a result, and may generate a side-effect.

Example expressions (1)

```
42  // Expression evaluating to value 42

17 + 42  // Expression evaluating to value 59
```

```
int a;

a = 23  // Expression evaluating to value 23
a + 17  // Expression evaluation to value 40
```

```
static_cast<float>(a)  // Expression evaluating to floating-point value 23.0f
```

Example expressions (2)

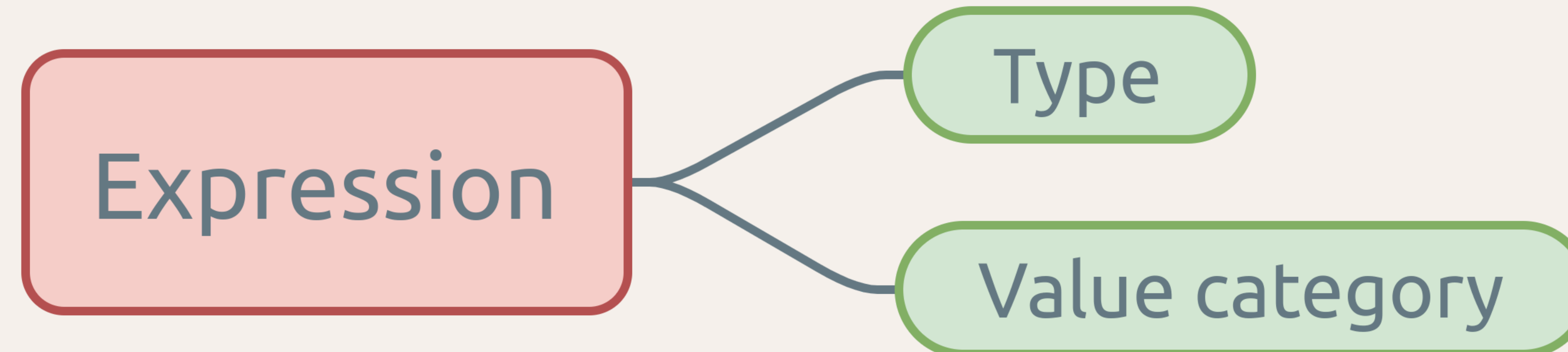
```
int a;

sizeof a  // Expression evaluating to the byte size of 'a'
          // Id-expression 'a' is unevaluated
```

```
[]{ return 3; }  // Expression evaluating to a closure
```

```
printf("Hi!\n")  // Expression evaluating to the number of characters written
                 // Result is often discarded, i.e. a 'discarded-value expression'
```

Expressions in C++

In C++, each expression is identified by two properties:



Primary value categories

`lvalue` – Locator value

`prvalue` – Pure `rvalue`

`xvalue` – eXpiring value

But wait...there's more!

`glvalue` – General `lvalue`

`rvalue` – errrRrr..value 🏴‍☠️

Back to expressions

Value categories are organized based on expression properties:

1. Does it evaluate to an identity?
2. Can its result resources be safely stolen?

Does it evaluate to an identity?

```
int a;

a  // Has identity
```

```
42                  // Has no identity
nullptr             // Has no identity
false               // Has no identity
[]{ return 42; }    // Has no identity
"Hi"                // Has identity
```

```
std::cout  // Has identity
```

```
a + 2      // Has no identity
a || true  // Has no identity
```

```
a++  // Has no identity
++a  // Has identity
```

```
static_cast<int>(a)  // Has no identity
std::move(a)         // Has identity
```

Can its resources be safely stolen?

Expression result resources can be stolen if it evaluates to an anonymous temporary, or if the associated object is near the end of its lifetime.

. . .

This was the main motivation for move semantics 🤔

Can its resources be safely stolen?

```
std::string func()
{
  return "Steal me!";
}

std::vector<std::string> vec;

vec.push_back(func());
```

```
std::string x{"Steal me!"};

std::vector<std::string> vec;

vec.push_back(std::move(x));
```

Let’s get organized!

Has **ID**	Has **no ID**

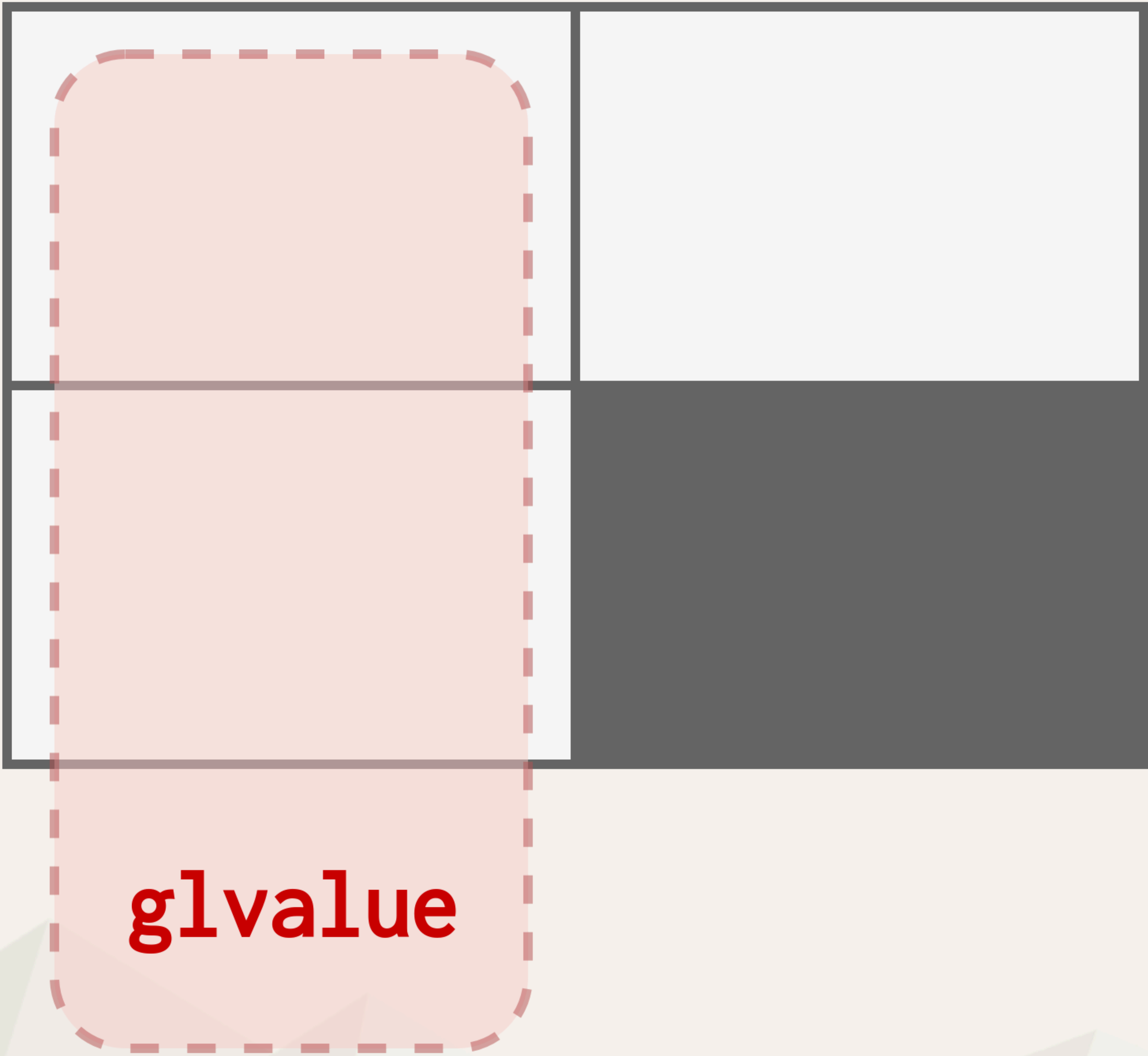
	Has **ID**	Has **no ID**
Can steal resources		
Cannot steal resources		

	Has **ID**	Has **no ID**
Can steal resources		
Cannot steal resources		

Has **ID** Has **no ID**

Can steal resources

Cannot steal resources



	Has ID	Has no ID
Can steal resources		`prvalue`
Cannot steal resources		

`glvalue`

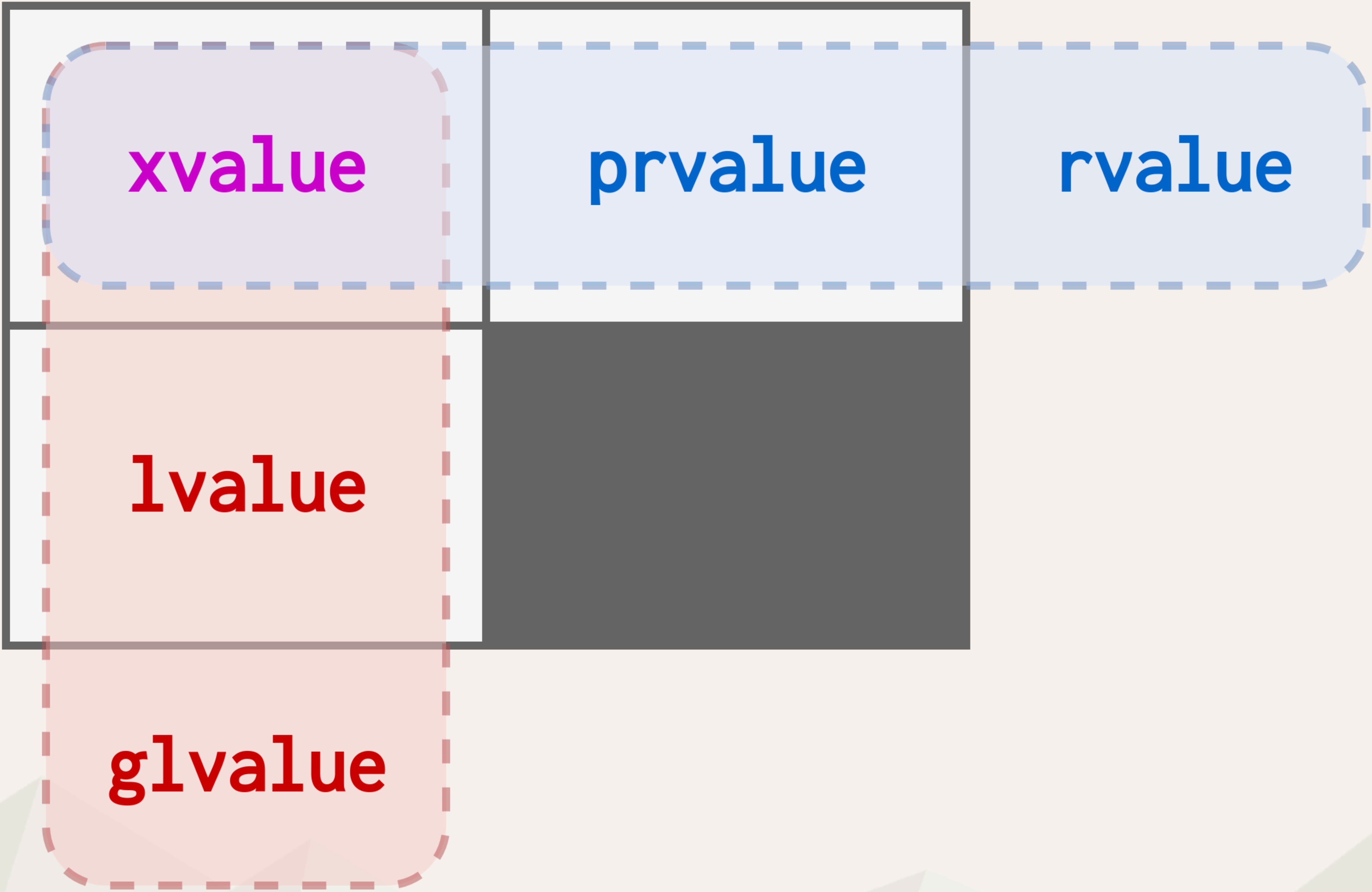
	Has ID	Has no ID
Can steal resources	xvalue	prvalue
Cannot steal resources		
	glvalue	

	Has ID	Has no ID
Can steal resources	xvalue	prvalue
Cannot steal resources	lvalue	
	glvalue	

Has **ID** Has **no ID**

Can steal resources

Cannot steal resources

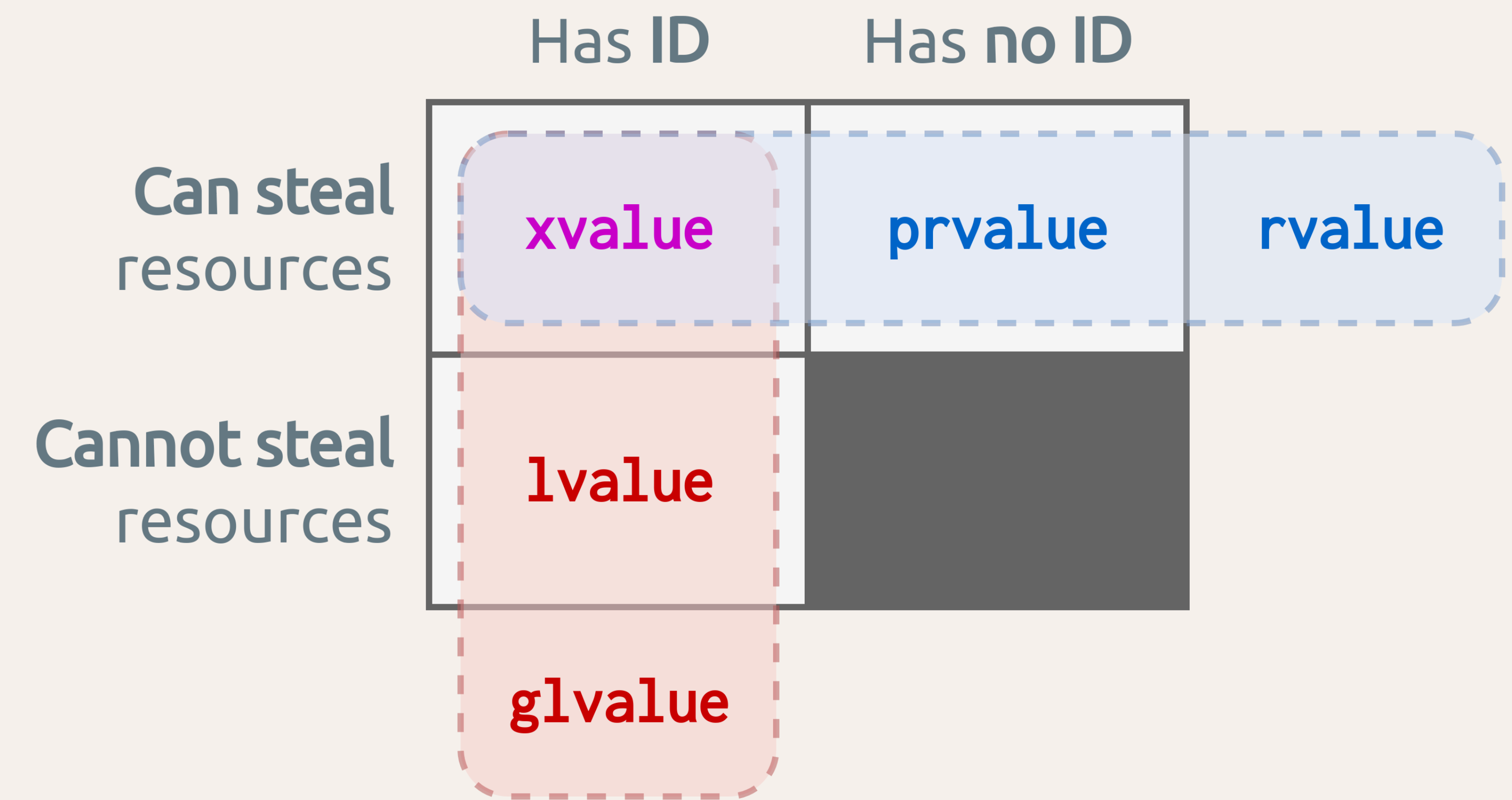


Examples (1)

```
42  // prvalue
```

```
nullptr  // prvalue
```

```
"Hi there!"  // lvalue
```

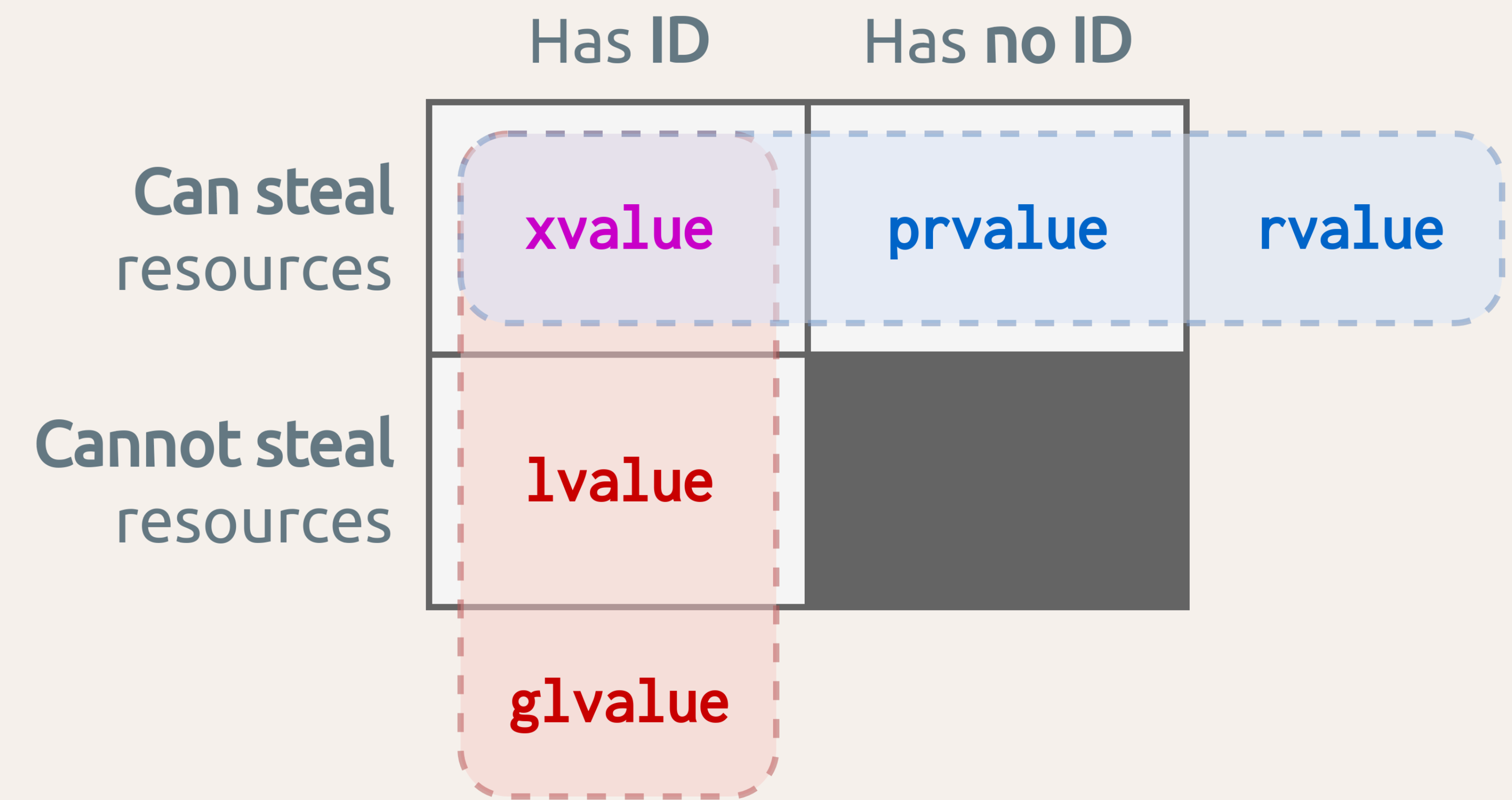


Examples (2)

```
int x = 42;
```

```
++x   // lvalue
```

```
x++   // prvalue
```

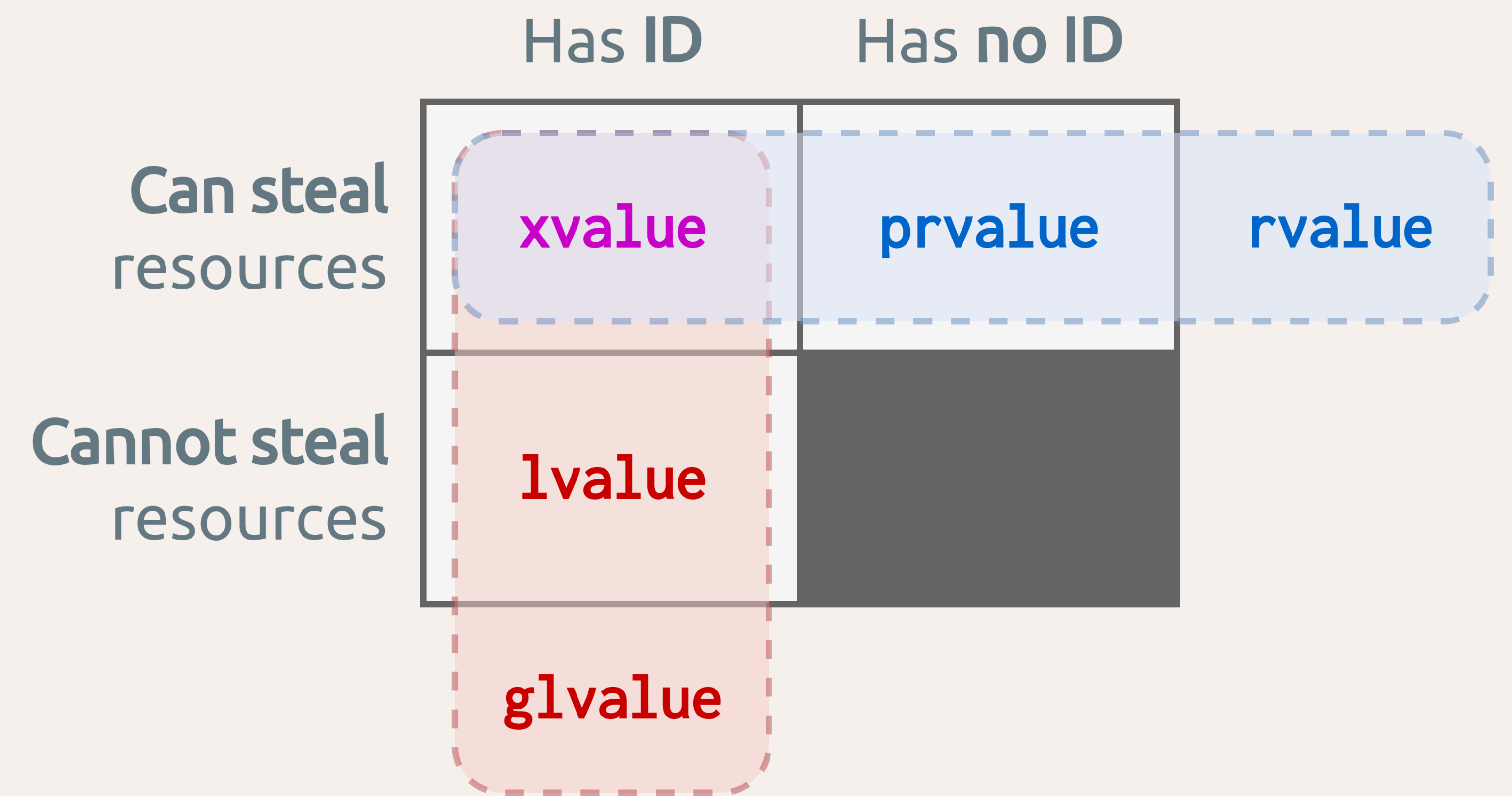


Examples (3)

```
int x = 42;
```

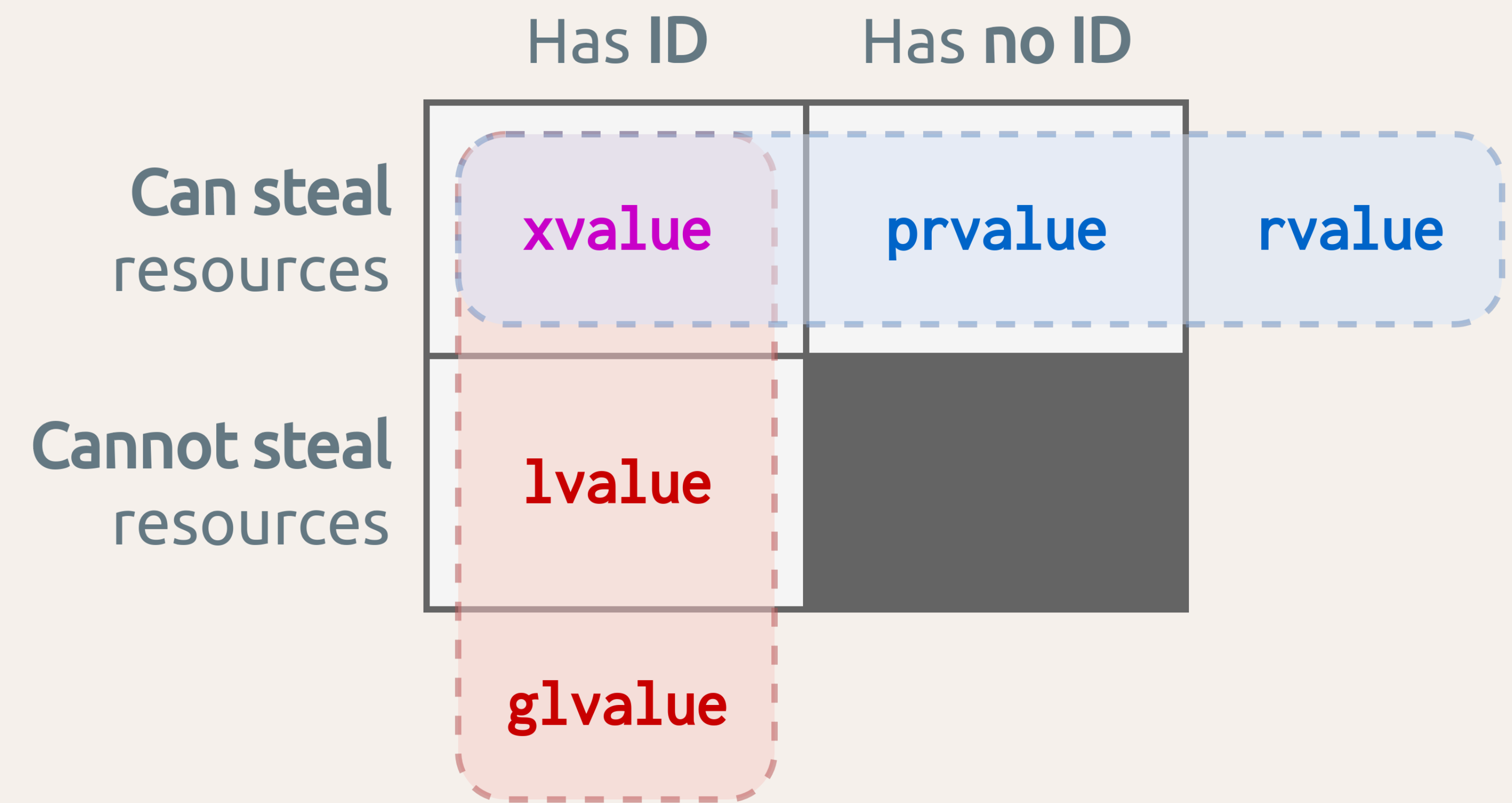
```
x    // lvalue
```

```
std::move(x)   // xvalue
```



Examples (4)

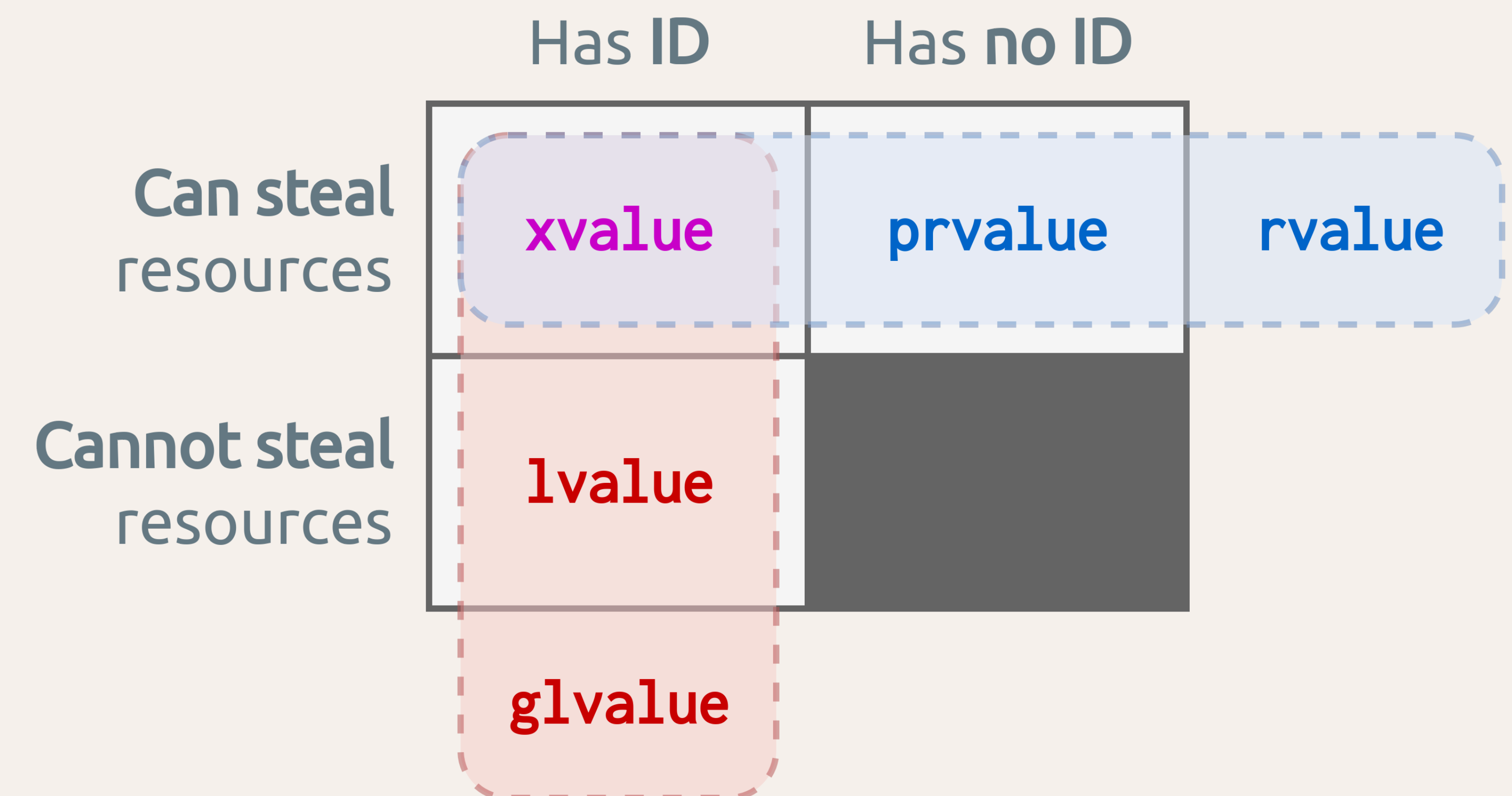
```
void func(int &&arg)
{
  // 'arg' is an lvalue

  // 'std::move(arg)' is an xvalue
  other_func(std::move(arg));
}

func(42);  // '42' is a prvalue
```



Examples (5)

```
void func(int &arg);    // #1
void func(int &&arg);   // #2
```

```
int &&x = 42;

func(x);  // Which overload is called?
```



Expression x is an **lvalue**; so overload #1 is called

A little side step: history

- CPL (1963) first introduced `lvalue` and `rvalue` concepts,
- Via BCPL and B came along C, keeping the definitions,
- C++ first followed the C definition up until C++03,
- C++11 introduced move semantics, changing it again.

Please forget the right-/left-hand notion for today's definition.

OK then. Now what?

- Communication: learn and be literate!
- Reading compiler errors effectively,
- Useful for understanding move semantics,
- Understanding copy elision and implicit conversions.

Quiz revisited

```
struct Number {
  int value_ = {};
};

class T {
public:
  T(const Number &n) : n_{n} {}

  T(const T &) { puts("Copy c'tor"); }

  Number get() { return n_; }

private:
  Number n_;
};
```

```
static T create(Number &&n) {
  return T{std::move(n)};
}

int main() {
  T x = T{create(Number{42})};

  return x.get().value_;
}
```

What's the output?

Questions?

Value categories in the wild

Copy elision

A section in the C++ standard that describes the elision (i.e. ***omission****) of copy/move operations, resulting in zero-copy pass-by-value semantics.*

Restrictions apply 😞

Copy elision

> ***Permits*** *elisions, it does not* ***guarantee****!*

Actual results depend on compiler and compiler settings.

Copy elision in action

C++ code:

```
T func()
{
  return T{};  // Create temporary
}

T x = func();  // Create temporary
```

Possible output (1):

```
T()
T(const &)
~T()
T(const &)
~T()
~T()
```

No copy elision.

Copy elision in action

C++ code:

```
T func()
{
  return T{};  // Create temporary?
}

T x = func();  // Create temporary?
```

Possible output (2):

```
T()
T(const &)
~T()
~T()
```

Partial copy elision.

Copy elision in action

C++ code:

```
T func()
{
  return T{};
}

T x = func();
```

Possible output (3):

```
T()
~T()
```

Full copy elision.

Where can elisions occur?

- In the initialization of an object,
- In a `return` statement,
- In a `throw` expression,
- In a `catch` clause.

Great stuff!

Truth is; compilers have been doing it for years.. 😏

Copy elision since C++17

C++17 added **mandates** to the standard, informally known as:

- “Guaranteed copy elision”,
- “Guaranteed return value optimization”,
- “Copy evasion”.

A set of special rules for `prvalue` expressions.

Guaranteed copy elision (1)

*If, in an initialization of an object, when the initializer expression is a **`prvalue`** of the same class type as the variable type.*

```
T x{T{}}; // Only one (default) construction of T allowed here
```

Guaranteed copy elision (2)

> *If, in a `return` statement the operand is a **`prvalue`** of the same class type as the function return type.*

```
T func()
{
  return T{};
}

T x{func()}; // Only one (default) construction of T allowed here
```

COMPILER EXPLORER

C++ source #1

--NORMAL--

```cpp
#include <cstdio>

struct T {
  T()         { puts(__PRETTY_FUNCTION__); }
  T(const T&) { puts(__PRETTY_FUNCTION__); }
  T(T&&)      { puts(__PRETTY_FUNCTION__); }
};

T factory() { return T{}; }

int main() {
  auto x = T{T{T{T{T{T{T{T{T{T{T{T{T{T{T{T{T{factory()}}}}}}}}}}}}}}}}};
}
```

x86-64 gcc 10.2 (Editor #1, Compiler #1) C++

x86-64 gcc 10.2 -O0

```asm
.LC0:
        .string "T::T()"
T::T() [base object constructor]:
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        mov     QWORD PTR [rbp-8], rdi
        mov     edi, OFFSET FLAT:.LC0
        call    puts
        nop
        leave
        ret
factory():
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        mov     QWORD PTR [rbp-8], rdi
        mov     rax, QWORD PTR [rbp-8]
        mov     rdi, rax
        call    T::T() [complete object constructor]
        mov     rax, QWORD PTR [rbp-8]
        leave
        ret
main:
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
```

Output (0/0) x86-64 gcc 10.2 - 991ms (26636B)

#1 with x86-64 gcc 10.2

```
ASM generation compiler returned: 0
Execution build compiler returned: 0
Program returned: 0
 T::T()
```

Under the hood

Under the rules of C++17, a `prvalue` *will be used only as an* ***unmaterialized recipe*** *of an object, until actual materialization is required.*

A `prvalue` *is an expression whose* ***evaluation initializes/materializes*** *an object.*

This is called a *temporary materialization conversion*.

Temporary materialization

```
struct Person {
  std::string name_;
  unsigned int age_ = {};
};

Person createPerson() {
  std::string name;
  unsigned int age = 0;

  // Get data from somewhere in runtime..

  return Person{name, age};    // 1. Initial prvalue expression
}

int main() {
  return createPerson().age_;  // 2. Temporary materialization: xvalue
}
```

Temporary materialization

An implicit **`prvalue`** *to* **`xvalue`** *conversion.*

`prvalue`s are not moved from!

C++17 copy/move elision

= Copy elision + temporary materialization

Return Value Optimization

AKA ‘RVO’

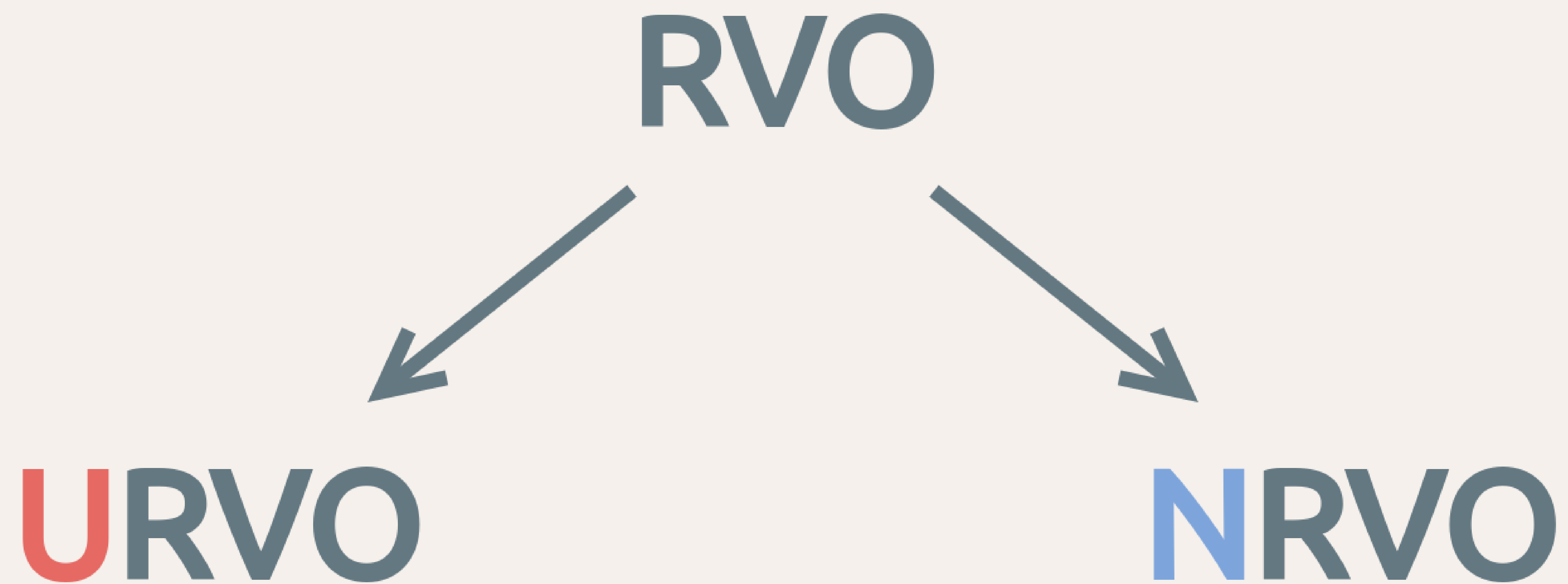
A variant of copy elision.

Return Value Optimization

Two forms:

1. Unnamed RVO (URVO or simply RVO),
2. Named RVO (NRVO).

Return Value Optimization



These terms live outside the standard.

Unnamed RVO (URVO)

Refers to the returning of temporary objects from a function.

***Guaranteed** by C++17 rules.*

Named RVO (NRVO)

Refers to the returning of named objects from a function.

NRVO in action

The most simple example

```
T func()
{
  T result;

  return result;
}

T x = func();
```

```
T()
~T()
```

NRVO in action

Slightly more involved

```
T func()
{
  T result;

  if (something)
    return result;

  // ...

  return result;
}

T x = func();
```

```
T()
~T()
```

It still works

NRVO is finicky though

NRVO is not always possible (1)

Multiple outputs

```
T func()
{
  T result;

  if (something)
    return {};  // prvalue

  return result; // lvalue
}

T x = func();
```

Output stored elsewhere

```
static T result;

T func()
{
  return result;
}

T x = func();
```

NRVO is not always possible (2)

Slicing 🍕

```
struct U : T { /* Additional members */ };

T func()
{
  U result;

  return result;
}

T x = func();
```

Returning a function argument

```
T func(T arg)
{
  return arg;
}

T x = func(T{});
```

Implicit move

When even NRVO is not possible..

```
T func(T arg)
{
  return arg;
}

T x = func(T{});
```

```
T()
T(&&)
~T()
~T()
```

Implicit **rvalue** conversion!

Guidelines

- Don’t be afraid to return an object by value,
- Don’t be too smart, let the compiler do the work for you,
- Implement your move constructor/`operator=`,
- Use compile-time programming if possible,
- Keep your functions short.

Quiz revisited

```
struct Number {
  int value_ = {};
};

class T {
public:
  T(const Number &n) : n_{n} {}

  T(const T &) { puts("Copy c'tor"); }

  Number get() { return n_; }

private:
  Number n_;
};
```

```
static T create(Number &&n) {
  return T{std::move(n)};
}

int main() {
  T x = T{create(Number{42})};

  return x.get().value_;
}
```

What's the output?

Quiz revisited

```cpp
struct Number {
  int value_ = {};
};

class T {
public:
  T(const Number &n) : n_{n} {}

  Number get() { return n_; }

private:
  Number n_;
};
```

```cpp
int main() {
  T x = T{Number{42}};

  return x.get().value_;
}
```

What’s the output?

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C++ source #1

A | Save/Load | Add new... | Vim | CppInsights | Quick-bench | C++

```cpp
#include <cstdio>
#include <utility>

struct Number {
  int value_ = {};
};

class T {
public:
  T(const Number &n) : n_{n} {}

  T(const T &) { puts("Copy c'tor"); }

  Number get() { return n_; }

private:
  Number n_;
};

static T create(Number &&n) {
  return T{std::move(n)};
}

int main() {
  T x = T{create(Number{42})};

  return x.get().value_;
}
```

x86-64 gcc 10.2 (Editor #1, Compiler #1) C++

x86-64 gcc 10.2 | -O1 -std=c++17

A | Output... | Filter... | Libraries | Add new... | Add tool...

```asm
main:
        mov     eax, 42
        ret
```

Output (0/0) x86-64 gcc 10.2 - 934ms (29896B)

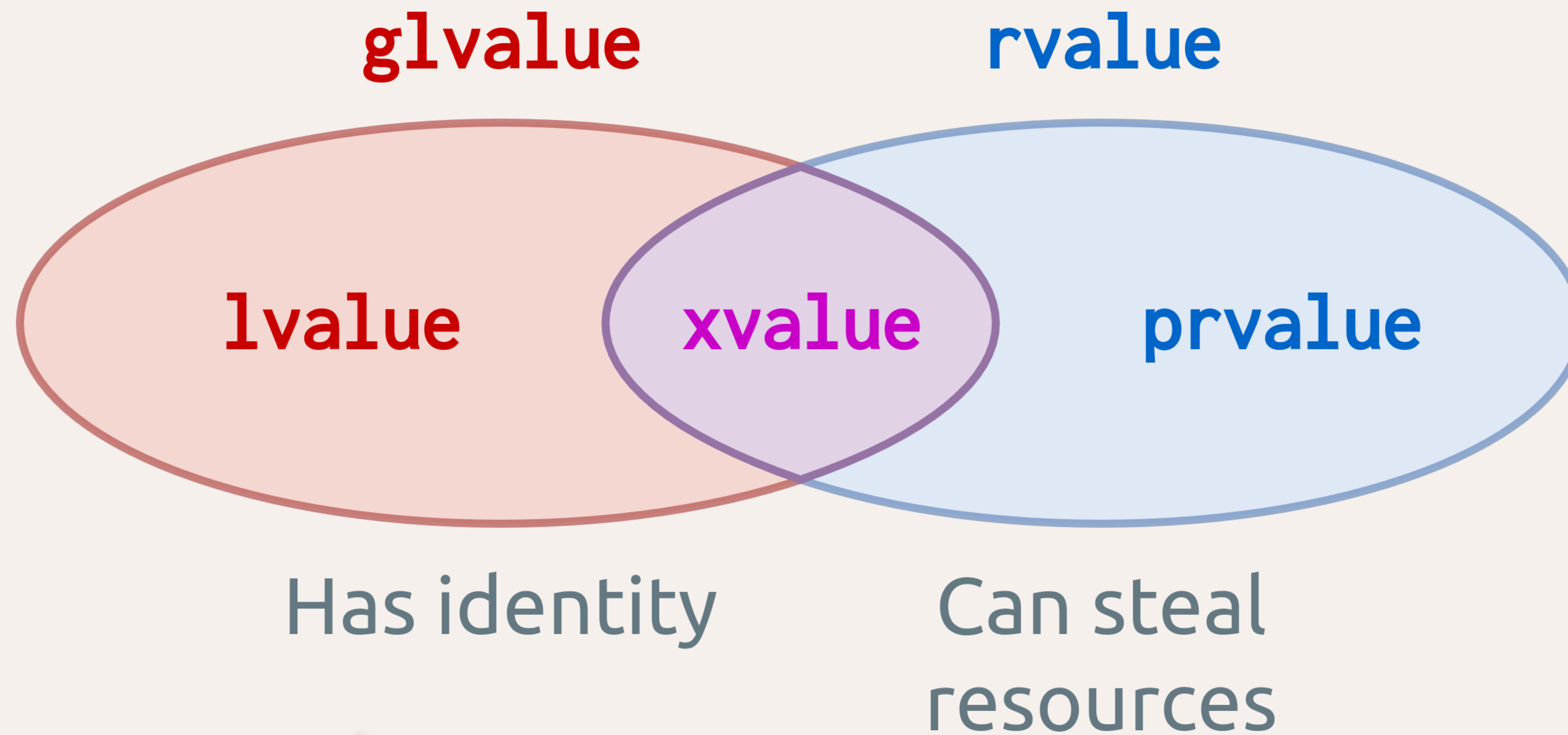
#1 with x86-64 gcc 10.2

A | Wrap lines

```
ASM generation compiler returned: 0
Execution build compiler returned: 0
Program returned: 42
```

Conclusions

C++ value categories



Copy/move elision / RVO

- **Copy elision**: part of the standard; permits,
- **Temporary materialization**: part of the standard; mandates,
- URVO and NRVO: unofficial terms.
- Implicit move: a RVO that happens even without copy elision,
- `prvalue`s are **not** moved from.

End

Thank you 😃