

# **ETC4500/ETC5450**

## **Advanced R programming**

Week 9: Object-oriented programming  
(vctrs)



# Outline

- 1 Programming paradigms
- 2 Object oriented programming

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# Programming paradigms

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- Functions are created and used like any other object.
- Output should only depend on the function's inputs.

# Programming paradigms

## Functional programming (W5)

- Functions are created and used like any other object.
- Output should only depend on the function's inputs.

## Object-oriented programming (W6-W7)

- Functions are associated with object types.
- Methods of the same 'function' produce object-specific output.

# Programming paradigms

## Literate programming (W7)

- Natural language is interspersed with code.
- Aimed at prioritising documentation/comments.
- Now used to create reproducible reports/documents.

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## Literate programming (W7)

- Natural language is interspersed with code.
- Aimed at prioritising documentation/comments.
- Now used to create reproducible reports/documents.

## Reactive programming (W8)

- Objects are expressed using code based on inputs.
- When inputs change, the object's value updates.



# Outline

- 1 Programming paradigms
- 2 Object oriented programming

# Object oriented programming

## S3

- The OO system used by most of CRAN.
- Very simple (and 'limited') compared to other systems.

# Object oriented programming

## S3

- The OO system used by most of CRAN.
- Very simple (and 'limited') compared to other systems.

## vctrs

- Builds upon S3 to make creating vectors easier.
- Good practices inherited by default.

## S3 Recap: Objects and methods

Unlike most OO systems where methods belong to **objects/data**, S3 methods *belong* to 'generic' **functions**.

Recall that functions in R are objects like any other.

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Recall that functions in R are objects like any other.

### Self awareness

In S3, there is no concept of 'self' since the relevant objects are available as function arguments.

However S3 is self-aware of registered methods, allowing `NextMethod()` to call the S3 method of the inherited class.

# S3 Recap: S3 dispatch

To use S3, we call the generic function (e.g. `plot()`).

```
plot
```

```
function (x, y, ...)  
UseMethod("plot")  
<bytecode: 0x5716ffbb04b0>  
<environment: namespace:base>
```

## S3 Recap: S3 dispatch

This function looks at the inputs and dispatches (uses) the appropriate method for the input variable class/type.

```
stats:::plot.density
```

```
function (x, main = NULL, xlab = NULL, ylab = "Density", type = "l",
  zero.line = TRUE, ...)
{
  if (is.null(xlab))
    xlab <- paste("N =", x$n, "  Bandwidth =", formatC(x$bw))
  if (is.null(main))
    main <- sub("[.]default", "", deparse(x$call))
  plot.default(x, main = main, xlab = xlab, ylab = ylab, type = type,
    ...)
  if (zero.line)
    abline(h = 0, lwd = 0.25, col = "gray")
  invisible(NULL)
}
```

## S3 Recap: S3 dispatch

If there isn't a registered method for the object, the default method for the generic will be used.

```
graphics::plot.default
```

```
function (x, y = NULL, type = "p", xlim = NULL, ylim = NULL,
  log = "", main = NULL, sub = NULL, xlab = NULL, ylab = NULL,
  ann = par("ann"), axes = TRUE, frame.plot = axes, panel.first = NULL,
  panel.last = NULL, asp = NA, xgap.axis = NA, ygap.axis = NA,
  ...)
{
  localAxis <- function(..., col, bg, pch, cex, lty, lwd) Axis(...)
  localBox <- function(..., col, bg, pch, cex, lty, lwd) box(...)
  localWindow <- function(..., col, bg, pch, cex, lty, lwd) plot.window(...)
  localTitle <- function(..., col, bg, pch, cex, lty, lwd) title(...)
  xlabel <- if (!missing(x))
    deparse1(substitute(x))
  ylabel <- if (!missing(y))
```



# Creating an S3 generic

S3 generics work like any ordinary function, but they include `UseMethod()` which calls the appropriate method.

## Your turn!

Create an S3 generic called “reverse”.

This function will reverse objects. For example,

- `reverse("stressed")` becomes "desserts",
- `reverse(7919)` becomes 9197,
- `reverse(1.9599)` becomes 9959.1.

# Writing S3 methods

An S3 method is an ordinary function with some constraints:

- The function's name is of the form `<generic>.<class>`,
- The function's arguments match the generic's arguments,
- The function is registered as an S3 method (for packages).

This looks like:

```
#' Documentation for the method
#' @method <generic> <class>
<generic>.<class> <- function(<generic args>, <method args>, ...) {
  # The code for the method
}
```

# Writing S3 methods

## Your turn!

Write methods for reversing character, integer, and double objects.

- `reverse("stressed")` becomes "desserts",
- `reverse(7919L)` becomes 9197L,
- `reverse(1.9599)` becomes 9959.1.

*Hint: `stringi::stri_reverse()` will reverse a string.*


*The integer and double methods should return an integer and double respectively.*

# Writing S3 defaults

What if we tried to reverse the current date;  
`reverse(Sys.Date())`?

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 Your turn!

Question: what should the default behaviour be?

# Writing S3 defaults

What if we tried to reverse the current date;  
`reverse(Sys.Date())`?

 Your turn!

Question: what should the default behaviour be?

- Raise an error?
- Return a reversed string?
- Something else entirely?

# Creating your own S3 objects

S3 methods are (*mostly*) dispatched based on the `class()`.

```
class("stressed")
```

```
[1] "character"
```

```
class(7919L)
```

```
[1] "integer"
```

```
class(1.9599)
```

```
[1] "numeric"
```

# Creating your own S3 objects

To create an S3 object, we add a class to an object.

This is usually done with `structure()`, for example:

```
e <- structure(list(numerator = 2721, denominator = 1001), class = "fraction")  
e
```

```
$numerator
```

```
[1] 2721
```

```
$denominator
```

```
[1] 1001
```

```
attr(,"class")
```

```
[1] "fraction"
```



# Creating your own S3 objects

The `structure()` function is usually only used within other functions made for end-users. For example,

- `lm()` returns a list with class `"lm"`, and
- `tibble()` returns a `data.frame` (list) with classes `"tbl_df"`, `"tbl"`, and `"data.frame"`.

# Creating your own S3 objects

The `structure()` function is usually only used within other functions made for end-users. For example,

- `lm()` returns a list with class `"lm"`, and
- `tibble()` returns a `data.frame` (list) with classes `"tbl_df"`, `"tbl"`, and `"data.frame"`.

## Your turn!

Create `fraction()`, which returns `fraction` objects.  
This function should check that the inputs are suitable

# Creating your own S3 objects

The `fraction` class doesn't yet have any methods, so it inherits methods from its list type.

Usually we would create a method for printing S3 objects.

```
print.fraction <- function(x, ...) {  
  paste(x$numerator, x$denominator, sep = "/")  
}  
e
```

2721/1001

# Creating your own S3 objects

## Your turn!

Create a `reverse()` method for the `fraction` object class, which inverts the numerator and denominator.

*Finished early?*

Write a method for converting a `fraction` into a number.

# Creating your own S3 vectors (with vctrs)

The `vctrs` package is helpful for creating custom vectors. It is built upon S3, so the same approach for creating S3 generics and S3 methods also applies to `vctrs`.



S3 or `vctrs`?

- Regular S3 is useful for creating singular objects
- `vctrs` is useful for creating vectorised objects

# Creating your own S3 vectors (with vctrs)

## Why vctrs?

*vctrs* simplifies the complicated parts in creating vectors

- easy subsetting
- nice printing
- predictable recycling
- casting / coercion
- tidyverse compatibility

# Examples of vctrs packages

Lots of vctrs including:

- IP addresses
- Spatial geometries
- Time
- uncertainty

<https://github.com/krlmlr/awesome-vctrs>

# Some packages I've made that use vctrs

- **distributional**

Distributions of various shapes in vectors

- **mixtime**

Time points/intervals of various granularities in vectors

- **graphvec**

Graph factors, storing graph edges between levels.

- **fabletools**

Custom data frames 'mable', 'fable', and 'dable'.



# Creating a new vctr

The basic way to produce a vctr is with `vctrs::new_vctr()`.

Just like `structure()`, you provide an object and its new class.

```
attendance <- vctrs::new_vctr(c(80, 70, 75, 50), class = "percent")  
attendance
```

```
<percent[4]>  
[1] 80 70 75 50
```

# Creating a new vctr

As with S3, functions provide ways for users to create vectors.

```
percent <- function(x) {  
  vctrs::new_vctr(x, class = "percent")  
}  
attendance <- percent(c(80, 70, 75, 50))  
attendance
```

```
<percent[4]>  
[1] 80 70 75 50
```

# Creating a new vctr

Don't forget to check the inputs, vctrs provides helpful functions to make this easier and provide informative errors.

```
percent <- function(x) {  
  vctrs::vec_assert(x, numeric())  
  vctrs::new_vctr(x, class = "percent")  
}  
percent("80%")
```

Error in `percent()`:  
! `x` must be a vector with type <double>.  
Instead, it has type <character>.

# Creating a new vctr

It's useful to provide default arguments in this function which creates a length 0 vector (similar to how empty vectors are created with `numeric()` and `character()`).

```
percent <- function(x = numeric()) {  
  vctrs::vec_assert(x, numeric())  
  vctrs::new_vctr(x, class = "percent")  
}  
percent()
```

```
<percent[0]>
```

# Creating a new vctr

While `vctrs` provides a nice `print` method, we need to specify how our vector should be formatted.

```
format.percent <- function(x, ...) {  
  paste0(vctrs::vec_data(x), "%")  
}  
attendance
```

```
<percent[4]>  
[1] 80% 70% 75% 50%
```

# The rcrd type

A special type of vctr is a record (rcrd).

A record is a list containing equal length vectors, and its size is the length its vectors rather than its list.

## Record indexing

Usually in R, indexing happens across the list. With the record type, indexing happens within the list's vectors.

# The rcrd type

## Length of a data frame

Usually the length of data refers to the number of rows, but in R it is the number of columns since it is a list.

```
length(mtcars)
```

```
[1] 11
```

In `vctrs`, data is a record so we get the number of rows.

```
vctrs::vec_size(mtcars)
```

```
[1] 32
```

# Creating a new rcrd

A record is created with the `vctrs::new_rcrd()` function.

```
wallet <- vctrs::new_rcrd(  
  list(amt = c(10, 38), unit = c("AU$", "¥")), class = "currency"  
)  
format.currency <- function(x, ...) {  
  paste0(vctrs::field(x, "unit"), vctrs::field(x, "amt"))  
}  
wallet
```

```
<currency[2]>  
[1] AU$10 ¥38
```



# Creating a new rcrd

## Your turn!

Rewrite the `fraction()` function to use the `rcrd` data type.

You will also need to update the methods:

- Obtain the numerator and denominator with `field()`.
- Replace the `print` method with a `format` method.
- Remove the `print.fraction` method with `rm()`.

# The list\_of type

`list_of()` vectors require list elements to be the same type.

It can be created with `list_of()`, or more easily converted to with `as_list_of()`. It behaves identically to `new_vctr()`.

```
vctrs::as_list_of(list(80, 70, 75, 50), .ptype = numeric())
```

```
<list_of<double>[4]>
```

```
[[1]]
```

```
[1] 80
```

```
[[2]]
```

```
[1] 70
```

```
[[3]]
```

```
[1] 75
```

```
[[4]]
```

# Prototypes

Notice the `.ptype` when we used `as_list_of()`?

`ptype` is shorthand for `prototype`, which is a size-0 vector.

## Prototype attributes!

Prototypes contains all relevant attributes of the object, such as class, dimension, and levels of factors.

# Prototypes

Obtain prototypes of a vector with `vctrs::vec_ptype()`.

```
vctrs::vec_ptype(1:10)
```

```
integer(0)
```

```
vctrs::vec_ptype(rnorm(10))
```

```
numeric(0)
```

```
vctrs::vec_ptype(factor(letters))
```


```
factor()
```

```
Levels: a b c d e f g h i j k l m n o p q r s t u v w x y z
```

```
vctrs::vec_ptype(attendance)
```

```
<percent[0]>
```

## vctr, rcrd, or list\_of?

 Your turn!

What's better? The `vctr` type or `list_of`?

# vctr, rcrd, or list\_of?

🔥 Your turn!

What's better? The `vctr` type or `list_of`?

It depends! If your vector is based on...

- a single atomic vector (like `percent`) then `vctr`,
- two or more atomic vectors (like `fraction`), then `rcrd`,
- complicated objects (like `lm`), then `list_of`.

# That's it! You have created a new vector for R!

**i** Time to celebrate with a break!

Ask questions, try using your new vector in various ways.

# Methods for vctrs

While our new vectors looks pretty and fits right in with our tidy tibbles, it isn't very useful yet.

## Adding features

Since vctrs is built upon S3, the same approach for creating generic functions and methods applies to vctrs.



# Methods for vctrs

While our new vectors looks pretty and fits right in with our tidy tibbles, it isn't very useful yet.

## Adding features

Since vctrs is built upon S3, the same approach for creating generic functions and methods applies to vctrs.

However there are also some important **vector specific methods** which should be written to improve usability.

# (Proto)typing

We saw earlier how R coerces vectors of different types.

```
c("desserts", 10)
```

```
[1] "desserts" "10"
```

```
c(pi, 0L)
```

```
[1] 3.14 0.00
```

```
c(-1, TRUE, FALSE)
```

```
[1] -1 1 0
```

```
c(1, Sys.Date())
```

```
[1] 1 20153
```

# (Proto)typing

When combining or comparing vectors of different types, R will (usually) *coerce* to the 'richest' type.



# (Proto)typing

vctrs doesn't make any assumptions about how to coerce your vector, and instead raises an error.

```
library(vctrs)  
vec_c(attendance, 0.8)
```

```
Error in `vec_c()`:  
! Can't combine `..1` <percent> and `..2` <double>.
```

# (Proto)typing

We can specify what the common ('richest') type is by writing `vctrs::vec_ptype2()` methods.

```
#' @export
vec_ptype2.percent.double <- function(x, y, ...) {
  percent() # Prototype since this produces size-0
}
vctrs::vec_ptype2(attendance, 0.8)
```

```
<percent[0]>
```

```
vctrs::vec_ptype2(0.8, attendance)
```

Error:

```
! Can't combine `0.8` <double> and `attendance` <percent>.
```

# (Proto)typing

Common typing uses *double-dispatch*.

We need to define the common type in both directions.

```
#' @export
vec_ptype2.double.percent <- function(x, y, ...) {
  percent() # Prototype since this produces size-0
}
vctrs::vec_ptype2(attendance, 0.8)
```

```
<percent[0]>
```

```
vctrs::vec_ptype2(0.8, attendance)
```

```
<percent[0]>
```

# (Proto)typing

 Your turn!

Write methods that define the common (proto)type between `fraction` and `double` as `fraction -> double`.

# Double dispatch

Unfortunately `c()` from base R can't (yet) be changed to support double-dispatch with S3. Usually this isn't a problem,

```
c(attendance, attendance)
```

```
<percent[8]>
```

```
[1] 80% 70% 75% 50% 80% 70% 75% 50%
```

```
c(attendance, 0.8)
```

```
<percent[5]>
```

```
[1] 80% 70% 75% 50% 0.8%
```



# Double dispatch

but if your class isn't used in the first argument...

```
c(0.8, attendance)
```

```
[1] 0.8 80.0 70.0 75.0 50.0
```

... your common (proto)type will be ignored!

# Double dispatch

vctrs uses double dispatch when needed, and using `vctrs::vec_c()` fixes many coercion problems in R.

```
vctrs::vec_c(0.8, attendance)
```

```
<percent[5]>
```

```
[1] 0.8% 80% 70% 75% 50%
```

```
vctrs::vec_c(1, Sys.Date())
```

```
Error in `vctrs::vec_c()`:
```

```
! Can't combine `..1` <double> and `..2` <date>.
```

# Double dispatch

## **i** Double dispatch inheritance

Double dispatch in vctrs doesn't work with inheritance and so:

- `NextMethod()` can't be used
- Default methods aren't inherited/used.

# Casting and coercion

## ! Converting percentages

Notice earlier how combining percentages with numbers gave the incorrect result?

This is because we haven't written a method for converting numbers into percentages.

The `vctrs::vec_cast()` generic is used to convert/coerce ('cast') one type into another. Time to write more methods!

# Casting and coercion

`vctrs::vec_cast()` also uses double dispatch.

```
vec_cast.double.percent <- function(x, to, ...) {  
  vec_data(x)/100  
}  
vec_cast.percent.double <- function(x, to, ...) {  
  percent(x*100)  
}  
  
vec_cast(0.8, percent())
```

```
<percent[1]>  
[1] 80%
```

```
vec_cast(percent(80), double())
```

```
[1] 0.8
```

# Casting and coercion

With both `vec_ptype2()` and `vec_cast()` methods for percentages and doubles it is now possible to combine them.

```
vctrs::vec_c(0.8, attendance)
```

```
<percent[5]>
```

```
[1] 80% 80% 70% 75% 50%
```

We can also use coercion to easily perform comparisons.

```
attendance > 0.7
```

```
[1] TRUE FALSE TRUE FALSE
```

# Casting and coercion

 Your turn!

Write a method for casting from a fraction to a double.  
Does this work with `as.numeric()`?

# Math and arithmetic

Methods also need to be written for math and arithmetic.

`vec_math()` implements mathematical functions like

```
mean(attendance)
```

```
<percent[1]>
```

```
[1] 68.75%
```

`vec_arith()` implements arithmetic operations like

```
attendance + percent(0.1)
```

```
Error in `vec_arith()` at vctrs/R/type-vctr.R:650:5:
```

```
! <percent> + <percent> is not permitted
```



# Math and arithmetic

Since attendance is a simple numeric, the default `vec_math` method works fine. The default `vec_math` function is essentially:

```
vec_math.percent <- function(.fn, .x, ...) {  
  out <- vec_math_base(.fn, .x, ...)  
  vec_restore(out, .x)  
}
```

- 1 Apply the math to the underlying numbers
- 2 Restore the percentage class

# Math and arithmetic

Unlike double dispatch in `vec_ptype2()` and `vec_cast()`, we currently need to implement our own secondary dispatch for `vec_arith()`.

```
vec_arith.percent <- function(op, x, y, ...) {  
  UseMethod("vec_arith.percent", y)  
}  
vec_arith.percent.default <- function(op, x, y, ...) {  
  stop_incompatible_op(op, x, y)  
}
```

# Math and arithmetic

Then we can create methods for arithmetic.

```
vec_arith.percent.percent <- function(op, x, y, ...) {  
  out <- vec_arith_base(op, x, y)  
  vec_restore(out, to = percent())  
}  
percent(40) + percent(20)
```

```
<percent[1]>  
[1] 60%
```

# Math and arithmetic

Then we can create methods for arithmetic.

```
vec_arith.percent.numeric <- function(op, x, y, ...) {  
  out <- vec_arith_base(op, x, vec_cast(y, percent()))  
  vec_restore(out, to = percent())  
}  
percent(40) + 0.3
```

```
<percent[1]>  
[1] 70%
```

```
0.3 + percent(40)
```

```
Error in `vec_arith()` at vctrs/R/type-vctr.R:650:5:  
! <double> + <percent> is not permitted
```

# Math and arithmetic

Then we can create methods for arithmetic.

```
vec_arith.numeric.percent <- function(op, x, y, ...) {  
  out <- vec_arith_base(op, vec_cast(x, percent()), y)  
  vec_restore(out, to = percent())  
}  
percent(40) + 0.3
```

```
<percent[1]>  
[1] 70%
```

```
0.3 + percent(40)
```

```
<percent[1]>  
[1] 70%
```

# Math and arithmetic

## Your turn!

Add support for math and arithmetic for the `fraction` class.

*Hint: cast your fraction to a double and then use the base `math/arith` function, returning a double is fine.*

*Finished early?*

Try to extend `vec_arith()` so that it retains the `fraction` class for `+`, `-`, `*`, `/` operations.