

APSTA-GE 2352

Statistical Computing: Lecture 11

Klinton Kanopka

New York University



NYU Grey Art Gallery

RIVER CENTER

WASHINGTON PL



Table of Contents

1. Statistical Computing - Week 11

1. Table of Contents

2. Announcements

2. Advanced Debugging

1. The tools we have so far

2. A more powerful debugging tool: `browser()`

3. The `apply()` Family

1. Side Effects

2. The `apply()` Family

3. Applying `apply()`

4. Wrap Up

Check-In

- PollEv.com/klintkanopka

Announcements

- PS6 is posted!
 - It's your 2nd to last pset
 - It's shorter than PS5
- Lab on Wednesday before Thanksgiving is cancelled
- After today:
 - 3 more lectures
 - 3 more labs
 - 2 more psets
- Reminder about next week's PRIISM seminar talk with my friend Charlie Rahal from Oxford!

Advanced Debugging

The tools we have so far

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- Do you feel like using generative AI to help with coding tasks increases your understanding?

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- What's your experience been with using ChatGPT to help you debug or write code?
- Are there other models/tools that you use?
- What prompting strategies do you use?
- Do you feel like using generative AI to help with coding tasks increases your understanding?
- Any other notes?

A more powerful debugging tool: `browser()`

- `browser()` lets you step into the code and execute it line by line while you monitor what is loaded in each environment and the values of intermediate objects
- You can further step into functions you encounter along the way
- How does it work?
 - You insert the `browser()` function call into some code you want to debug
 - From here, the right pane shows you the values and variables for the environment you're currently executing code in
 - You get a special prompt in the console, `Browse[1]>` to let you know you're doing browser stuff
 - All execution halts and the next line to be run appears above the prompt

Using browser()

- First, you can use the `Browse[1]>` prompt like any other sort of console prompt and execute code from there
- Second, and more importantly, you get access to a bunch of new commands:
 1. `n` runs the **next** line of code (whatever is currently above the prompt)
 2. `s` is like next, but if the next line is a function, you'll **step into** it and run it interactively (line-by-line)
 3. `c` stops running code line-by-line and **continues** executing the current function you're currently in
 4. `Q` **quits** out of the browser

Why and how to use `browser()`?

- Essentially it's not too far off from inserting `print()` statements after every single line
- It allows you to see what changes after each line of code is run
- You can also insert code into a function to see if it fixes your problem
- A few other ways to use it:
 - Running `debug(FUN())` inserts `browser()` into the first line of `FUN()`, and so running `FUN()` will *always* open the browser. Stop this with `undebug(FUN())`
 - `debugonce(FUN(args))` runs `FUN(args)` immediately opening a browser, but doesn't modify `FUN()`

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- Essentially it's not too far off from inserting `print()` statements after every single line
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 - Running `debug(FUN())` inserts `browser()` into the first line of `FUN()`, and so running `FUN()` will *always* open the browser. Stop this with `undebug(FUN())`
 - `debugonce(FUN(args))` runs `FUN(args)` immediately opening a browser, but doesn't modify `FUN()`
- **Next let's use `browser()` with the activity from lab yesterday**

The `apply()` Family

Side Effects

- If a function or operation modifies things outside its local environment, it has “side effects”
- These side effects can be hard to observe, but cause serious errors in analysis!
- Side effects most often occur when we are trying to hack together a solution to a problem
 - Functions that take and modify information from the global environment
 - Janky loops

Avoiding Side Effects

- Writing things in functions is a good start!
 - Calls to functions generate new environments
 - New environments protect data in the global environment
- We can “hide loops”
 - The `apply()` family of functions does this really well
 - These nest the entire loop we want to carry out inside of a function call

The `apply()` Family

- `apply()` takes a function and applies it to each element of a data object
- Whole bunch of different `apply()` functions
 - Different functions take different data objects as input
 - Different functions spit out different data objects
- Note that `apply()` functions aren't really any faster than loops!
 - They are not vectorized
 - They are, however, very easy to *parallelize*

The main `apply()` functions

function	input	output	comment
<code>apply()</code>	matrix or array	vector or array or list	
<code>lapply()</code>	list or vector	list	
<code>sapply()</code>	list or vector	vector or matrix or list	simplify
<code>vapply()</code>	list or vector	vector or matrix or list	safer simplify
<code>tapply()</code>	data, categories	array or list	ragged
<code>mapply()</code>	lists and/or vectors	vector or matrix or list	multiple

Applying `apply()`

Uncertainty in mean estimates

- First we conduct a simulation study to observe how the uncertainty in estimating the mean of a normal distribution depends on the number of samples we draw from it

```
1 # TODO
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Uncertainty in mean estimates

- First we conduct a simulation study to observe how the uncertainty in estimating the mean of a normal distribution depends on the number of samples we draw from it

```
1 Ns <- seq(from = 50, to = 1000, by = 50)
2 M <- 1000
3 means <- list(length = length(Ns))
4
5 for (i in seq_along(Ns)) {
6
7 }
```

Uncertainty in mean estimates

- First we conduct a simulation study to observe how the uncertainty in estimating the mean of a normal distribution depends on the number of samples we draw from it

```
1 Ns <- seq(from = 50, to = 1000, by = 50)
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5 for (i in seq_along(Ns)) {
6   for (j in 1:M) {
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8 }
9 }
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8     means[[i]][j] <- mean(rnorm(Ns[i]))
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12 d_mean <- data.frame(n = , mean = do.call(c, means))
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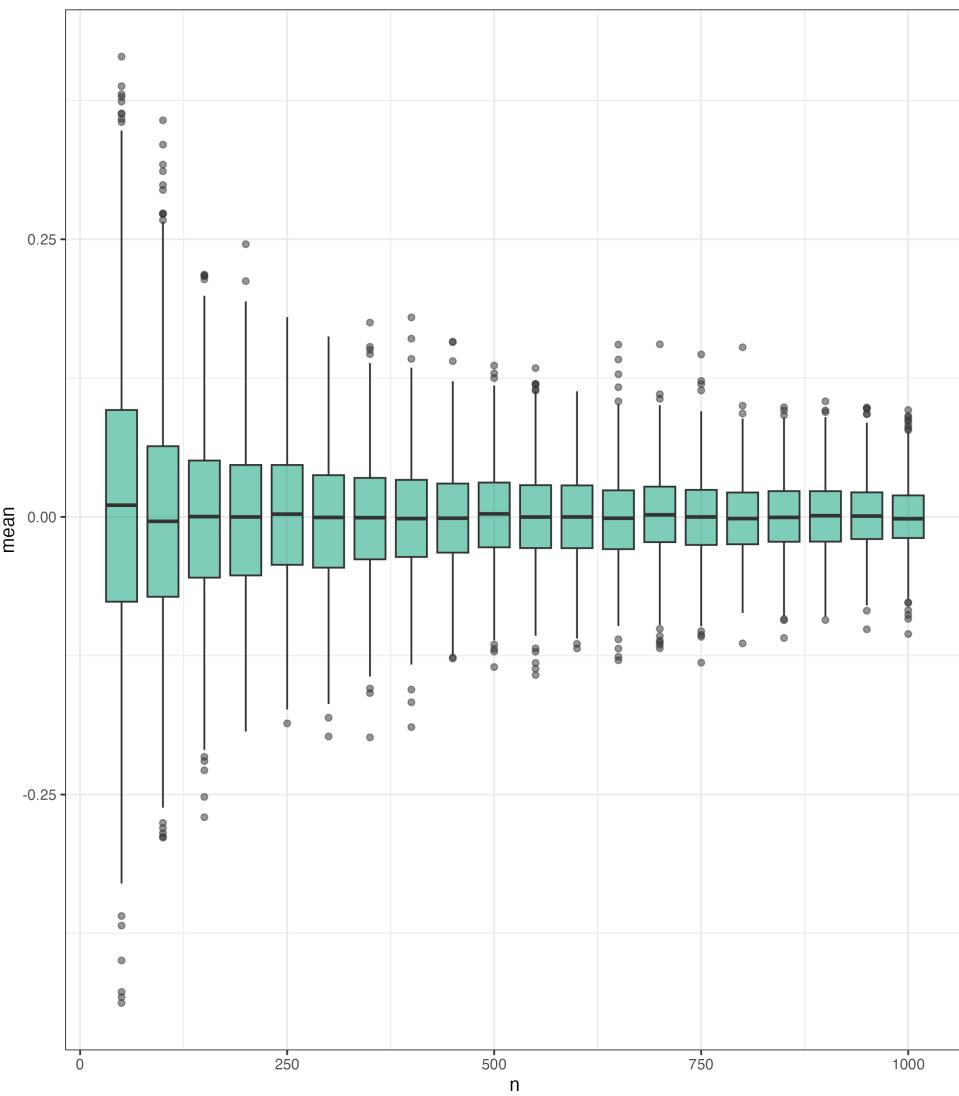
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12 d_mean <- data.frame(n = rep(Ns, each = M), mean = do.call(c, means))
```

Visualizing uncertainty in mean estimates

```
1 ggplot(d_mean, aes(x = n,
2                     y = mean,
3                     group = n)) +
4   geom_boxplot(alpha = 0.5,
5               fill = okabeito_colors(3)) +
6   theme_bw()
```



Estimating uncertainty directly

- Next we visualize our estimates of the standard errors of these sampling distributions at each sample size

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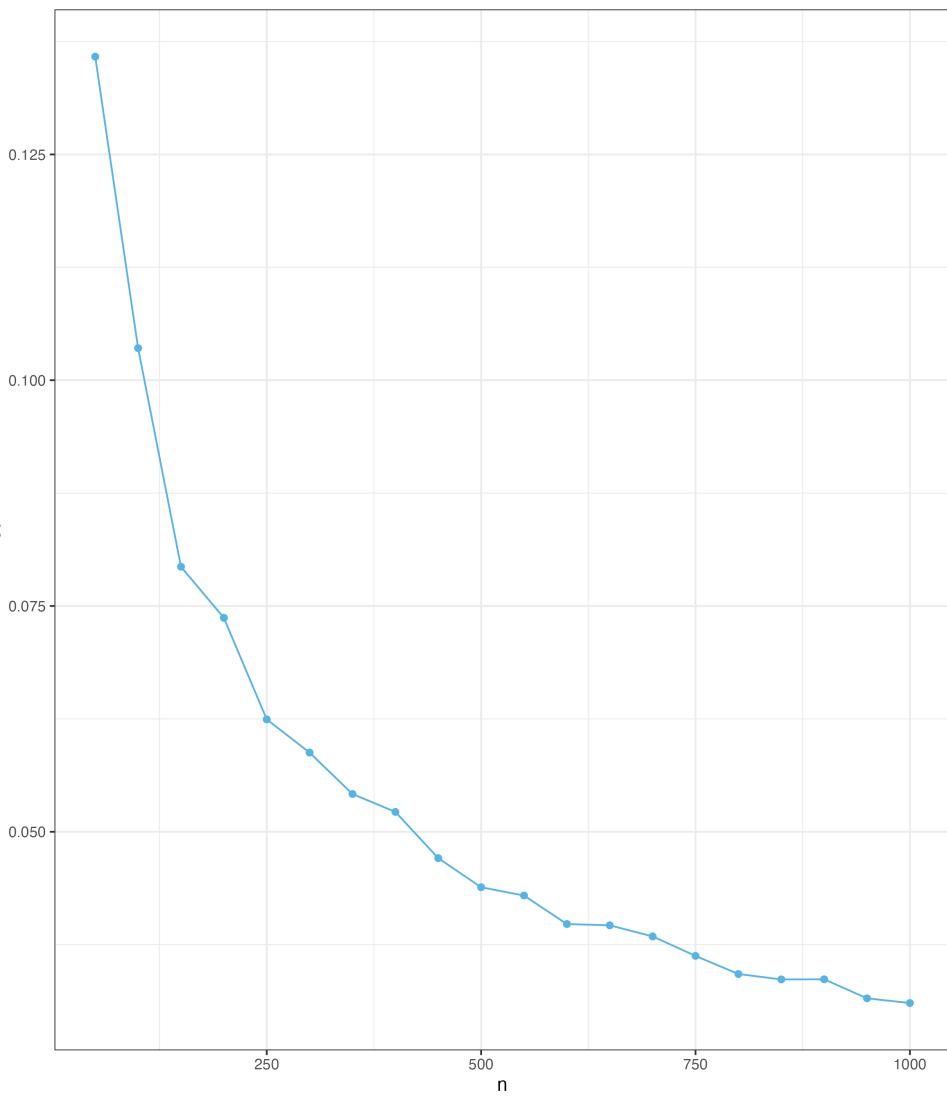
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Visualizing uncertainty estimates

```
1 ggplot(d_sd, aes(x = n, y = sd)) +  
2   geom_point(color = okabeito_colors(2)) +  
3   geom_line(color = okabeito_colors(2)) +  
4   theme_bw()
```



Uncertainty in mean estimates with `apply()`

- Now we redo the first simulation with something from the `apply()` family

```
1 # TODO: Write a simulation function  
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3 # TODO: Construct the object to apply() over  
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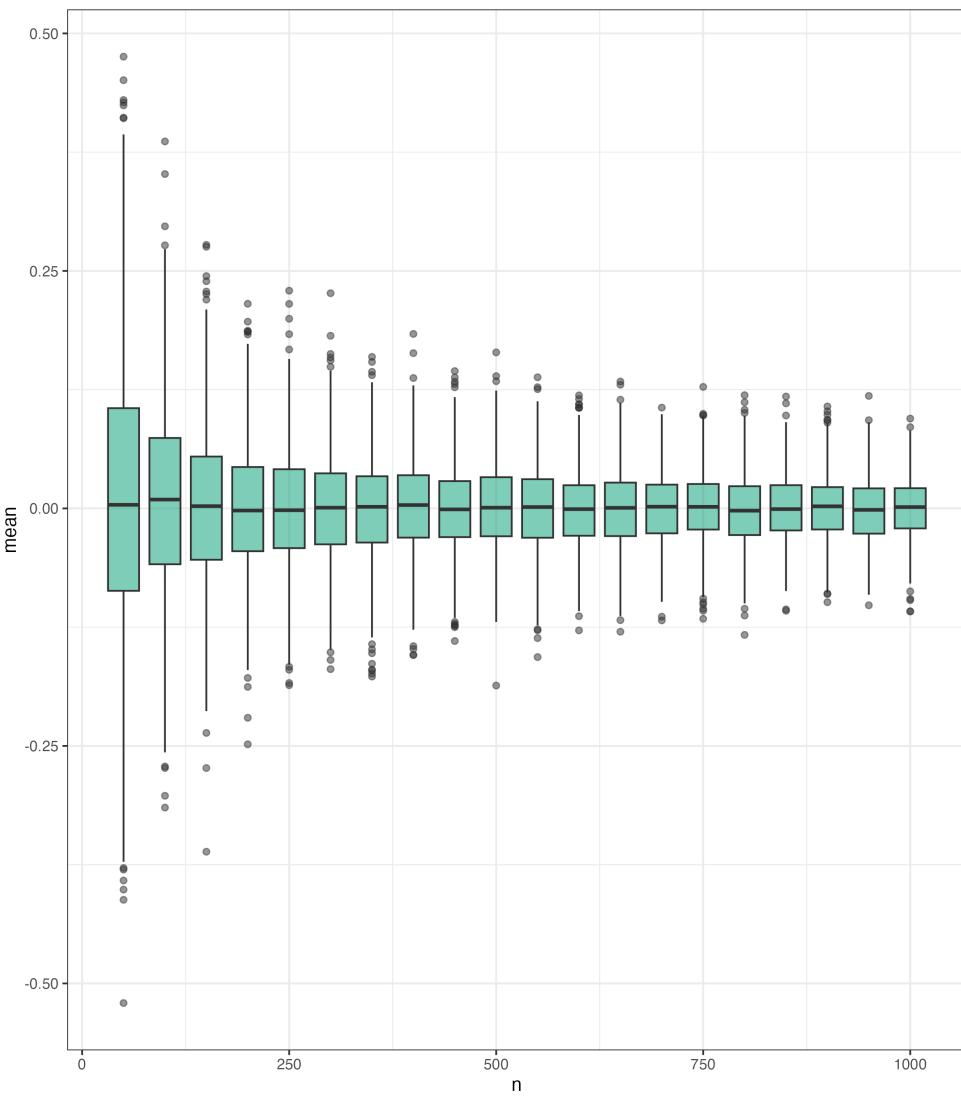
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Estimating uncertainty directly with `apply()`

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9 # TODO: Construct the output
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```
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3 SimFun2 <- function() {
4   return(sdev)
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1 # TODO: Write a simulation function
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3 SimFun2 <- function() {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
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16 # TODO: Construct the output
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4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 sim_control_2 <- data.frame(n_draws = Ns, n_reps = M)
15
16 # TODO: Construct the output
```

Estimating uncertainty directly with `apply()`

```
1 # TODO: Write a simulation function
2
3 SimFun2 <- function(n_draws, n_reps) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 sim_control_2 <- data.frame(n_draws = Ns, n_reps = M)
15
16 # TODO: Construct the output
17
18 sim_control_2$sd <- mapply(FUN = , ...)
```

Estimating uncertainty directly with `apply()`

```
1 # TODO: Write a simulation function
2
3 SimFun2 <- function(n_draws, n_reps) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 sim_control_2 <- data.frame(n_draws = Ns, n_reps = M)
15
16 # TODO: Construct the output
17
18 sim_control_2$sd <- mapply(FUN = SimFun2, ...)
```

Estimating uncertainty directly with `apply()`

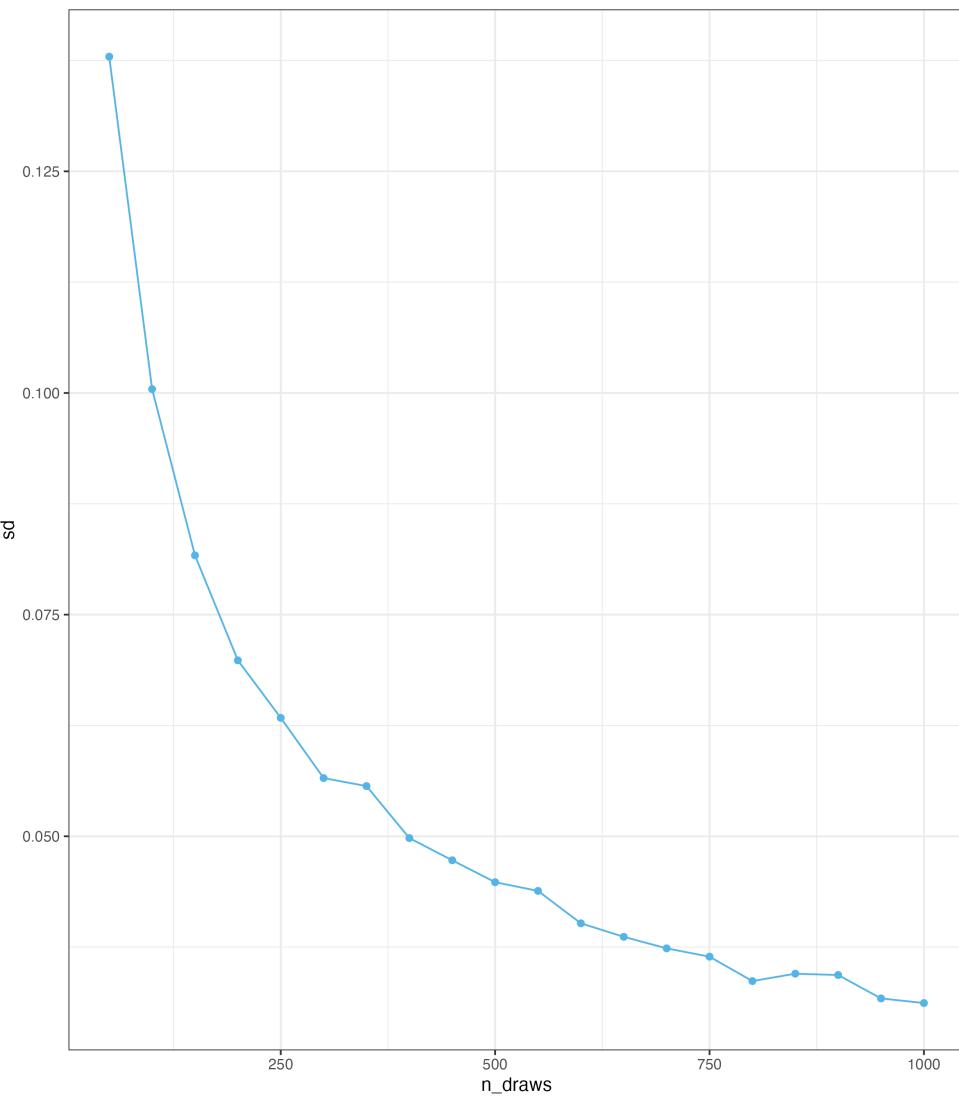
```
1 # TODO: Write a simulation function
2
3 SimFun2 <- function(n_draws, n_reps) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 sim_control_2 <- data.frame(n_draws = Ns, n_reps = M)
15
16 # TODO: Construct the output
17
18 sim_control_2$sd <- mapply(FUN = SimFun2,
19                             sim_control_2$n_draws,
20                             ...)
```

Estimating uncertainty directly with `apply()`

```
1 # TODO: Write a simulation function
2
3 SimFun2 <- function(n_draws, n_reps) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 sim_control_2 <- data.frame(n_draws = Ns, n_reps = M)
15
16 # TODO: Construct the output
17
18 sim_control_2$sd <- mapply(FUN = SimFun2,
19                             sim_control_2$n_draws,
20                             sim_control_2$n_reps)
```

Visualizing uncertainty estimates with apply()

```
1 ggplot(sim_control_2, aes(x = n_draws,
2                             y = sd)) +
3   geom_point(color = okabeito_colors(2)) +
4   geom_line(color = okabeito_colors(2)) +
5   theme_bw()
```



Extending to more distributions

```
1 # TODO: Write a simulation function  
2  
3 # TODO: Construct the object to apply() over  
4  
5 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun2 <- function(n_draws, n_reps) {
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5                   nrow = n_draws,
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7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
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10 }
11
12 # TODO: Construct the object to apply() over
13
14 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
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13
14 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- matrix(rnorm(n = n_draws * n_reps),
5                   nrow = n_draws,
6                   ncol = n_reps)
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
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10 }
11
12 # TODO: Construct the object to apply() over
13
14 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   # TODO: draw from distribution
5   # TODO: reshape into matrix
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
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13 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   # TODO: draw from distribution
5   draws <- do.call()
6   # TODO: reshape into matrix
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
10 }
11
12 # TODO: Construct the object to apply() over
13
14 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   # TODO: draw from distribution
5   draws <- do.call(what = , args = )
6   # TODO: reshape into matrix
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
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Extending to more distributions

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1 # TODO: Write a simulation function
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3 SimFun3 <- function(n_draws, n_reps, dist) {
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5   draws <- do.call(what = dist, args = )
6   # TODO: reshape into matrix
7   means <- apply(X = draws, MARGIN = 2, FUN = mean)
8   sdev <- sd(means)
9   return(sdev)
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Extending to more distributions

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1 # TODO: Write a simulation function
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5   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
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9   return(sdev)
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Extending to more distributions

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6   # TODO: reshape into matrix
7   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
8   means <- apply(X = draws, MARGIN = 2, FUN = mean)
9   sdev <- sd(means)
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Extending to more distributions

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3 SimFun3 <- function(n_draws, n_reps, dist) {
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6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
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Extending to more distributions

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6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 sim_control_3 <- data.frame()
14
15 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
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5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame()
15
16 # TODO: Construct the output
```

Extending to more distributions

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1 # TODO: Write a simulation function
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3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
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7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = ,
15                               n_reps = ,
16                               distribution = )
17
18 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
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3 SimFun3 <- function(n_draws, n_reps, dist) {
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6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = rep(Ns, times = length(distributions)),
15                               n_reps = ,
16                               distribution = )
17
18 # TODO: Construct the output
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = rep(Ns, times = length(distributions)),
15                               n_reps = M,
16                               distribution = )
17
18 # TODO: Construct the output
```

Extending to more distributions

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3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
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13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = rep(Ns, times = length(distributions)),
15                               n_reps = M,
16                               distribution = rep(distributions, each = length(Ns)))
17
18 # TODO: Construct the output
```

Extending to more distributions

```
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2
3 SimFun3 <- function(n_draws, n_reps, dist) {
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5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the object to apply() over
12
13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = rep(Ns, times = length(distributions)),
15                               n_reps = M,
16                               distribution = rep(distributions, each = length(Ns)))
17
18 # TODO: Construct the output
19
20 sim_control_3$sd <- mapply(FUN = , ...)
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
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13 distributions <- c('rnorm', 'runif', 'rexp')
14 sim_control_3 <- data.frame(n_draws = rep(Ns, times = length(distributions)),
15                               n_reps = M,
16                               distribution = rep(distributions, each = length(Ns)))
17
18 # TODO: Construct the output
19
20 sim_control_3$sd <- mapply(FUN = SimFun3,
21                             ...)
```

Extending to more distributions

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
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7   sdev <- sd(means)
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15                             n_reps = M,
16                             distribution = rep(distributions, each = length(Ns)))
17
18 # TODO: Construct the output
19
20 sim_control_3$sd <- mapply(FUN = SimFun3,
21                             sim_control_3$n_draws,
22                             ...)
```

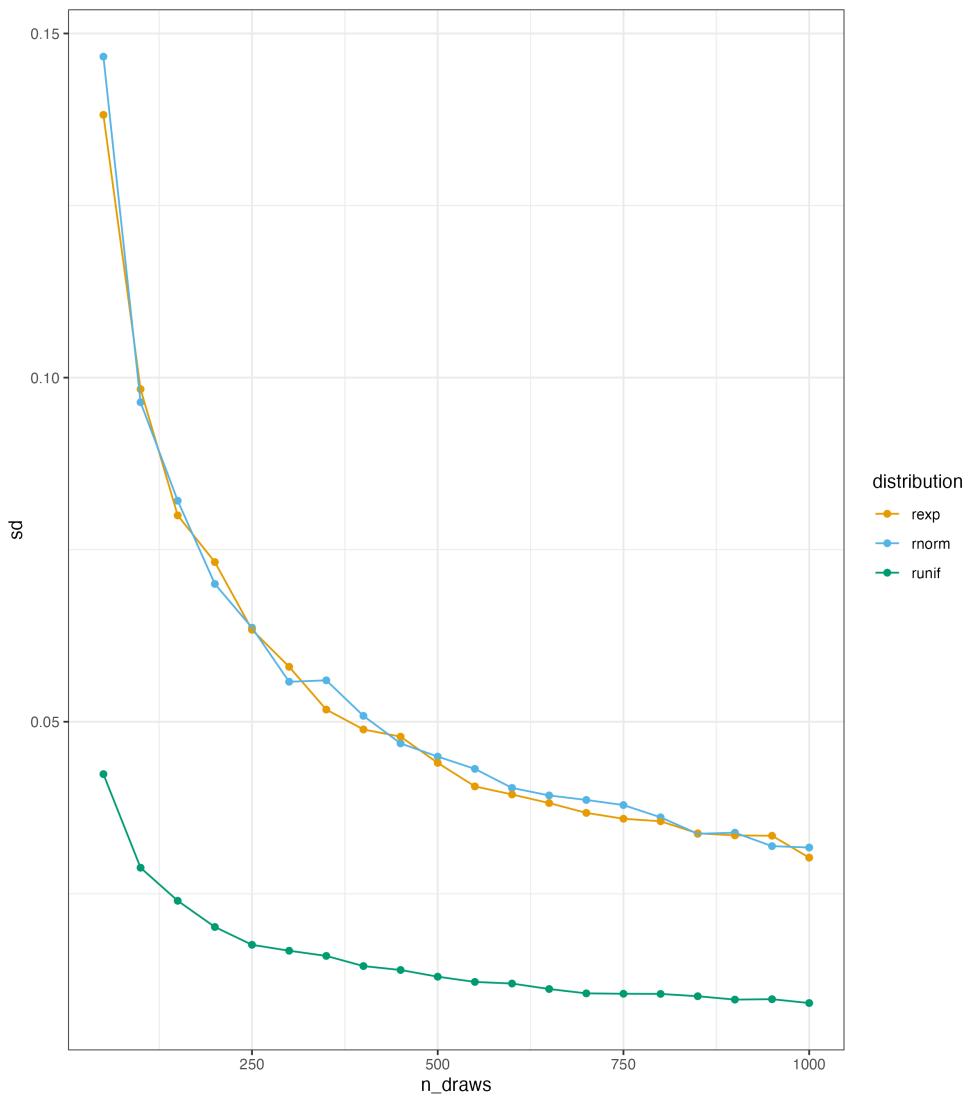
Extending to more distributions

```
1 # TODO: Write a simulation function
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3 SimFun3 <- function(n_draws, n_reps, dist) {
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15                             n_reps = M,
16                             distribution = rep(distributions, each = length(Ns)))
17
18 # TODO: Construct the output
19
20 sim_control_3$sd <- mapply(FUN = SimFun3,
21                             sim_control_3$n_draws,
22                             sim_control_3$n_reps,
23                             ...)
```

Extending to more distributions

Visualizing uncertainty across distributions

```
1 ggplot(sim_control_3,
2         aes(x = n_draws,
3               y = sd,
4               color = distribution)) +
5   geom_point() +
6   geom_line() +
7   scale_color_okabeito() +
8   theme_bw()
```



Constructing more complex data frame output

```
1 # TODO: Write a simulation function  
2  
3 # TODO: Construct the output
```

Constructing more complex data frame output

```
1 # TODO: Write a simulation function
2
3 SimFun3 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   sdev <- sd(means)
8   return(sdev)
9 }
10
11 # TODO: Construct the output
```

Constructing more complex data frame output

```
1 # TODO: Write a simulation function
2
3 SimFun4 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   out <- data.frame()
8   return(out)
9 }
10
11 # TODO: Construct the output
```

Constructing more complex data frame output

```
1 # TODO: Write a simulation function
2
3 SimFun4 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   out <- data.frame(n = , dist = , mean = )
8   return(out)
9 }
10
11 # TODO: Construct the output
```

Constructing more complex data frame output

```
1 # TODO: Write a simulation function
2
3 SimFun4 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(what = dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
7   out <- data.frame(n = n_draws, dist = , mean = )
8   return(out)
9 }
10
11 # TODO: Construct the output
```

Constructing more complex data frame output

```
1 # TODO: Write a simulation function
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3 SimFun4 <- function(n_draws, n_reps, dist) {
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6   means <- apply(X = draws, MARGIN = 2, FUN = mean)
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Constructing more complex data frame output

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7   out <- data.frame(n = n_draws, dist = dist, mean = means)
8   return(out)
9 }
10
11 # TODO: Construct the output
```

Constructing more complex data frame output

```
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Constructing more complex data frame output

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8 }
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10 # TODO: Construct the output
11
12 out <- mapply(FUN = , ...)
```

Constructing more complex data frame output

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13   FUN = SimFun4,
14   ...
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```

Constructing more complex data frame output

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7   return(out)
8 }
9
10 # TODO: Construct the output
11
12 out <- mapply(
13   FUN = SimFun4,
14   sim_control_3$n_draws,
15   ...
16 )
```

Constructing more complex data frame output

```
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3 SimFun4 <- function(n_draws, n_reps, dist) {
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14   sim_control_3$n_draws,
15   sim_control_3$n_reps,
16   ...
17 )
```

Constructing more complex data frame output

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6   out <- data.frame(n = n_draws, dist = dist, mean = apply(X = draws, MARGIN = 2, FUN = mean))
7   return(out)
8 }
9
10 # TODO: Construct the output
11
12 out <- mapply(
13   FUN = SimFun4,
14   sim_control_3$n_draws,
15   sim_control_3$n_reps,
16   sim_control_3$distribution
17 )
```

Constructing more complex data frame output

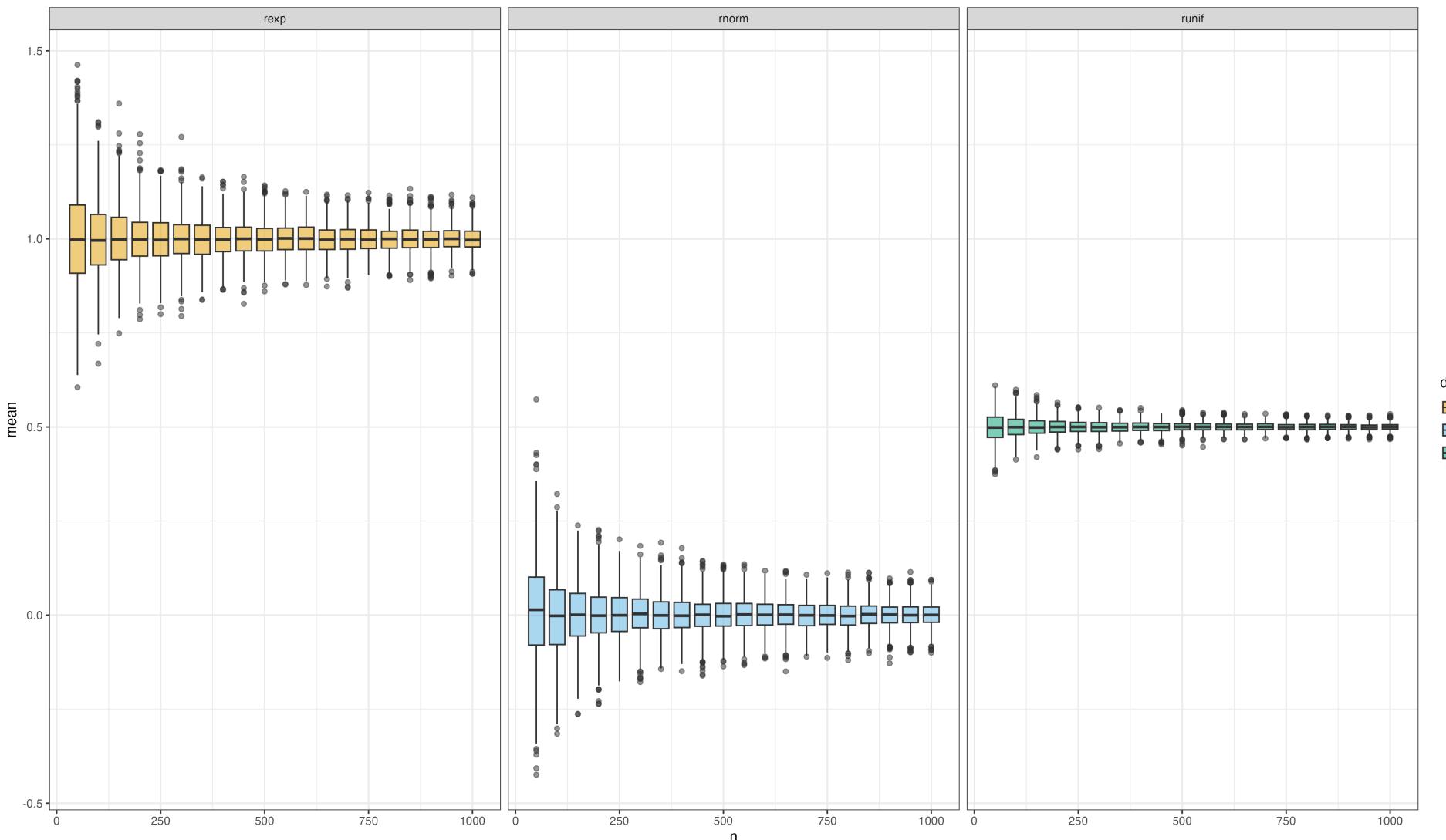
```
1 # TODO: Write a simulation function
2
3 SimFun4 <- function(n_draws, n_reps, dist) {
4   draws <- do.call(dist, args = list(n = n_draws * n_reps))
5   draws <- matrix(draws, nrow = n_draws, ncol = n_reps)
6   out <- data.frame(n = n_draws, dist = dist, mean = apply(X = draws, MARGIN = 2, FUN = mean))
7   return(out)
8 }
9
10 # TODO: Construct the output
11
12 out <- mapply(
13   FUN = SimFun4,
14   sim_control_3$n_draws,
15   sim_control_3$n_reps,
16   sim_control_3$distribution,
17   SIMPLIFY = FALSE
18 )
```

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20 d_sim_4 <- do.call('rbind', out)
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16                 SIMPLIFY = FALSE)
17
18 d_sim_4 <- do.call('rbind', out)
19
20 ggplot(d_sim_4, aes(x = n, y = mean, group = n, fill = dist)) +
21   geom_boxplot(alpha = 0.5) +
22   facet_grid(. ~ dist) +
23   scale_fill_okabeito() +
24   theme_bw()
```



Wrap Up

Recap

- Debugging is challenging, but we have four (five?) main tools:
 - Googling error messages
 - `print()` statements
 - `traceback()`
 - `browser()`
 - Maybe ChatGPT if you like it?
- The `apply()` family of functions allows you to hide loops
 - Not more efficient, but *safer* than loops
 - Encourages functionalization of code
 - Makes code easier to read

Final Thoughts

- PollEv.com/klintkanopka