

Case study: asphalt

The asphalt data

- ▶ 31 asphalt pavements prepared under different conditions. How does quality of pavement depend on these?
- ▶ Variables:
 - ▶ `pct.a.surf` Percentage of asphalt in surface layer
 - ▶ `pct.a.base` Percentage of asphalt in base layer
 - ▶ `finer` Percentage of fines in surface layer
 - ▶ `voids` Percentage of voids in surface layer
 - ▶ `rut.depth` Change in rut depth per million vehicle passes
 - ▶ `viscosity` Viscosity of asphalt
 - ▶ run 2 data collection periods: 1 for run 1, 0 for run 2.
- ▶ `rut.depth` response. Depends on other variables, how?

Packages for this section

```
library(MASS, exclude = "select")  
library(tidyverse)  
library(broom)  
library(leaps)
```

Make sure to load MASS before tidyverse (for annoying technical reasons), or to load MASS excluding its select (as above).

Getting set up

```
my_url <- "http://ritsokiguess.site/datafiles/asphalt.txt"  
asphalt <- read_delim(my_url, " ")
```

- ▶ Quantitative variables with one response: multiple regression.
- ▶ Some issues here that don't come up in "simple" regression; handle as we go. (STAB27/STAC67 ideas.)

The data (some)

```
asphalt
```

```
# A tibble: 31 x 7
```

	pct.a.surf	pct.a.base	finer	voids	rut.depth	viscosity	<dbl>
	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
1	4.68	4.87	8.4	4.92	6.75	2.8	
2	5.19	4.5	6.5	4.56	13	1.4	
3	4.82	4.73	7.9	5.32	14.8	1.4	
4	4.85	4.76	8.3	4.86	12.6	3.3	
5	4.86	4.95	8.4	3.78	8.25	1.7	
6	5.16	4.45	7.4	4.40	10.7	2.9	
7	4.82	5.05	6.8	4.87	7.28	3.7	
8	4.86	4.7	8.6	4.83	12.7	1.7	
9	4.78	4.84	6.7	4.86	12.6	0.92	
10	5.16	4.76	7.7	4.03	20.6	0.68	

```
# i 21 more rows
```

Plotting response “rut depth” against everything else

Same idea as for plotting separate predictions on one plot:

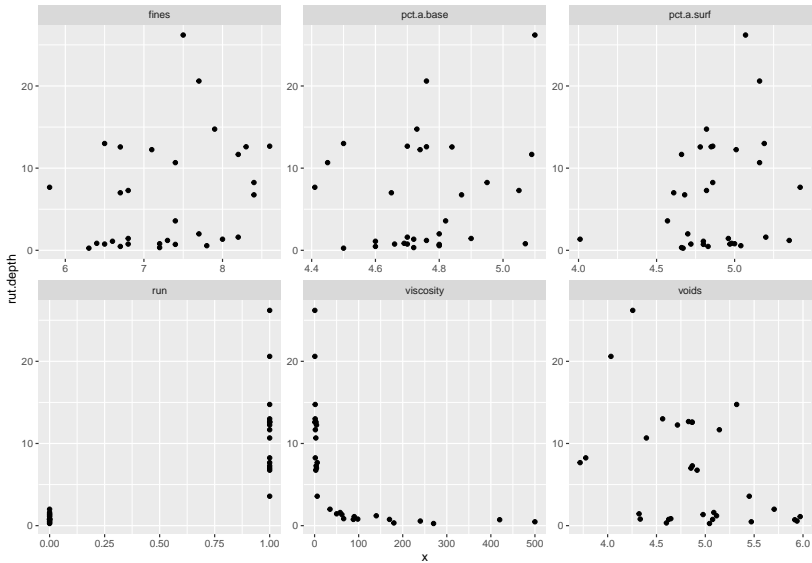
```
asphalt %>%  
  pivot_longer(  
    -rut.depth,  
    names_to="xname", values_to="x"  
  ) %>%  
  ggplot(aes(x = x, y = rut.depth)) + geom_point() +  
  facet_wrap(~xname, scales = "free") -> g
```

“collect all the x-variables together into one column called x, with another column xname saying which x they were, then plot these x’s against rut.depth, a separate facet for each x-variable.”

I saved this graph to plot later (on the next page).

The plot

g



Interpreting the plots

- ▶ One plot of rut depth against each of the six other variables.
- ▶ Get rough idea of what's going on.
- ▶ Trends mostly weak.
- ▶ `viscosity` has strong but non-linear trend.
- ▶ `run` has effect but variability bigger when `run` is 1.
- ▶ Weak but downward trend for `voids`.
- ▶ Non-linearity of `rut.depth-viscosity` relationship should concern us.

Log of viscosity: more nearly linear?

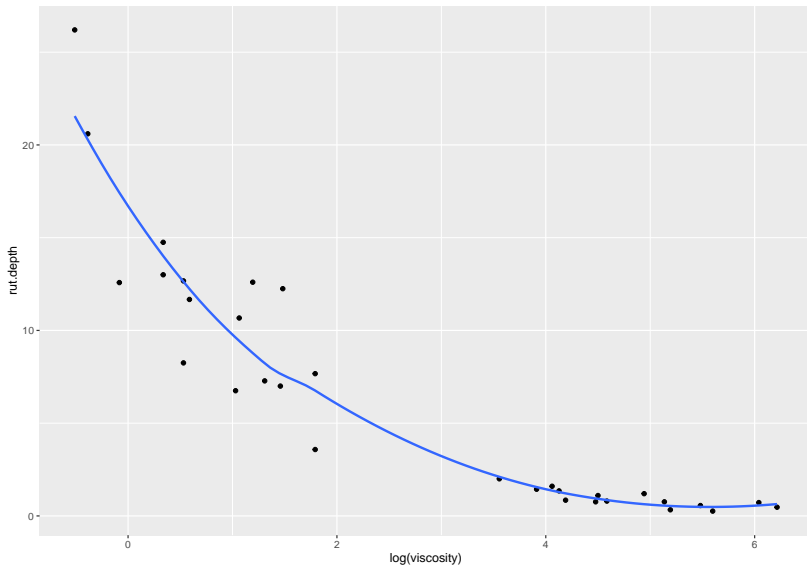
- Take this back to asphalt engineer: suggests log of viscosity:

```
ggplot(asphalt, aes(y = rut.depth, x = log(viscosity))) +  
  geom_point() + geom_smooth(se = FALSE) -> g
```

(plot overleaf)

Rut depth against log-viscosity

g



Comments and next steps

- ▶ Not very linear, but better than before.
- ▶ In multiple regression, hard to guess which x's affect response. So typically start by predicting from everything else.
- ▶ Model formula has response on left, squiggle, explanatories on right joined by plusses:

```
rut.1 <- lm(rut.depth ~ pct.a.surf + pct.a.base + fines +  
  voids + log(viscosity) + run, data = asphalt)  
summary(rut.1)
```

Call:

```
lm(formula = rut.depth ~ pct.a.surf + pct.a.base + fines +  
  log(viscosity) + run, data = asphalt)
```

Residuals:

	Min	1Q	Median	3Q	Max
	-4.1211	-1.9075	-0.7175	1.6382	9.5947

Regression output: summary(rut.1) or:

```
glance(rut.1)
```

```
# A tibble: 1 x 12
```

	r.squared	adj.r.squared	sigma	statistic	p.value	df	logLik	AI
	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
1	0.806	0.758	3.32	16.6	0.000000174	6	-77.3	171

```
# i 3 more variables: deviance <dbl>, df.residual <int>, nobs <int>
```

```
tidy(rut.1)
```

```
# A tibble: 7 x 5
```

	term	estimate	std.error	statistic	p.value
	<chr>	<dbl>	<dbl>	<dbl>	<dbl>
1	(Intercept)	-13.0	26.2	-0.496	0.625
2	pct.a.surf	3.97	2.50	1.59	0.125
3	pct.a.base	1.26	3.97	0.318	0.753
4	finest	0.116	1.01	0.115	0.909
5	voids	0.589	1.32	0.445	0.660
6	log(viscosity)	-3.15	0.919	-3.43	0.00220
7	run	-1.97	3.65	-0.539	0.595

Comments

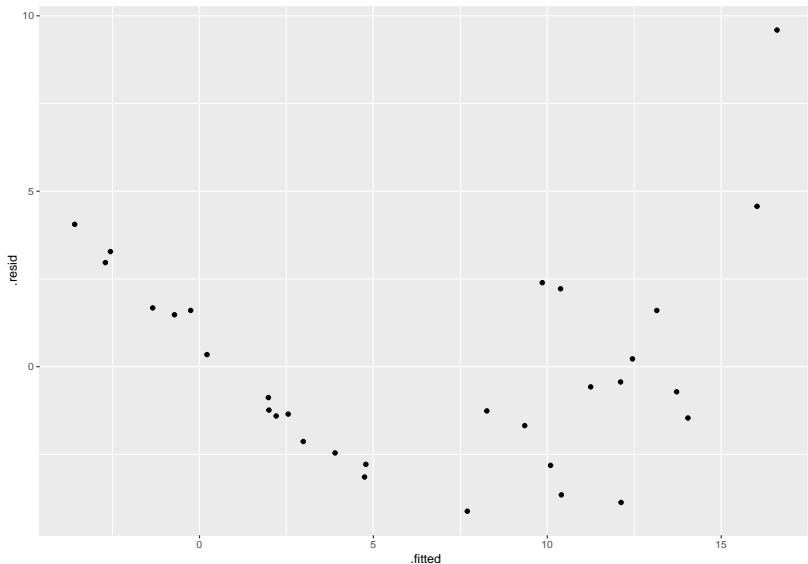
- ▶ R-squared 81%, not so bad.
- ▶ P-value in `glance` asserts that something helping to predict `rut.depth`.
- ▶ Table of coefficients says `log(viscosity)`.
- ▶ But confused by clearly non-significant variables: remove those to get clearer picture of what is helpful.

Before we do anything, look at residual plots:

- ▶ (a) of residuals against fitted values (as usual)
- ▶ (b) of residuals against each explanatory.
- ▶ Problem fixes:
 - ▶ with (a): fix response variable;
 - ▶ with some plots in (b): fix those explanatory variables.

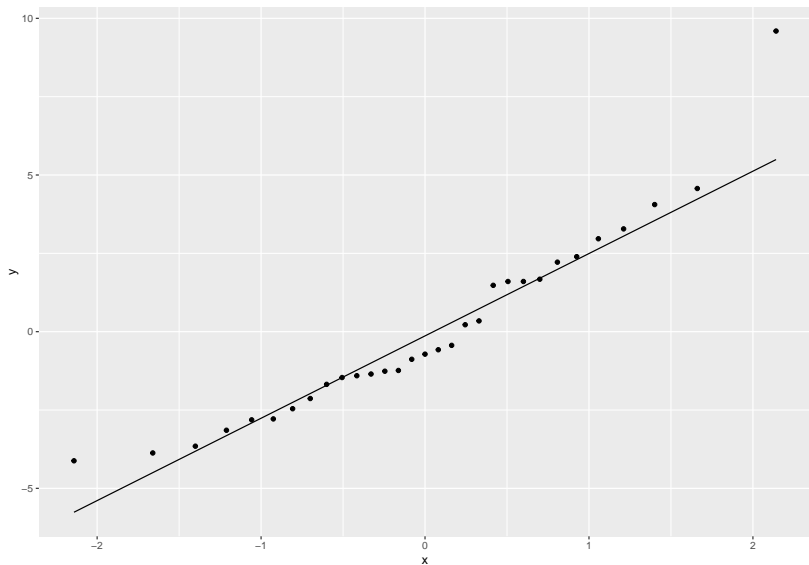
Plot fitted values against residuals

```
ggplot(rut.1, aes(x = .fitted, y = .resid)) + geom_point()
```



Normal quantile plot of residuals

```
ggplot(rut.1, aes(sample = .resid)) + stat_qq() + stat_qq_line()
```



Plotting residuals against x variables

- ▶ Problem here is that residuals are in the fitted model, and the observed x -values are in the original data frame `asphalt`.
- ▶ Package `broom` contains a function `augment` that combines these two together so that they can later be plotted: start with a model first, and then `augment` with a data frame:

```
rut.1 %>% augment(asphalt) -> rut.1a  
rut.1a
```

```
# A tibble: 31 x 13
```

	pct.a.surf	pct.a.base	fines	voids	rut.depth	viscosity	<dbl>
	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
1	4.68	4.87	8.4	4.92	6.75	2.8	
2	5.19	4.5	6.5	4.56	13	1.4	
3	4.82	4.73	7.9	5.32	14.8	1.4	
4	4.85	4.76	8.3	4.86	12.6	3.3	
5	4.86	4.95	8.4	3.78	8.25	1.7	
6	5.16	4.45	7.4	4.40	10.7	2.9	
7	4.82	5.05	6.8	4.87	7.28	3.7	

What does rut.1a contain?

```
names(rut.1a)
```

```
[1] "pct.a.surf" "pct.a.base" "fines"      "voids"      "1"  
[6] "viscosity"  "run"         ".fitted"    ".resid"     "  
[11] ".sigma"     ".cooksd"     ".std.resid"
```

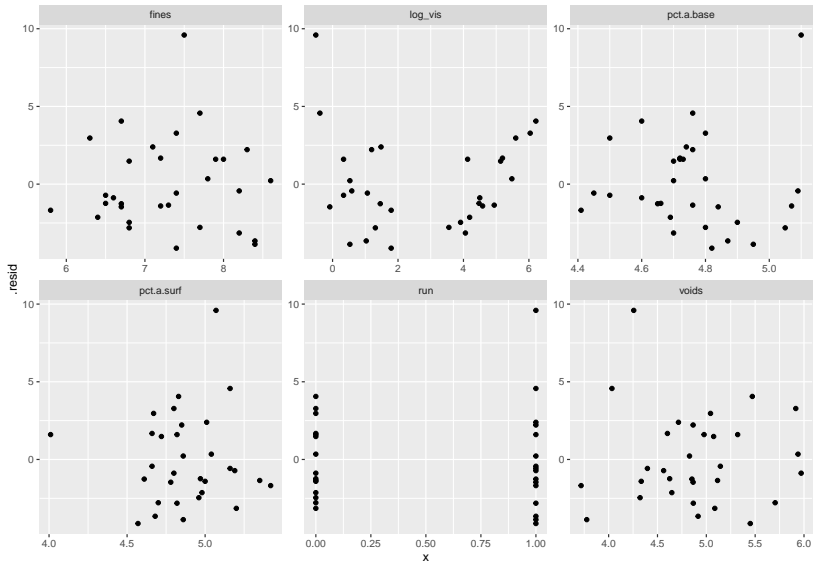
- ▶ all the stuff in original data frame, plus:
- ▶ quantities from regression (starting with a dot)

Plotting residuals against x -variables

```
rut.1a %>%  
  mutate(log_vis=log(viscosity)) %>%  
  pivot_longer(  
    c(pct.a.surf:voids, run, log_vis),  
    names_to="xname", values_to="x"  
  ) %>%  
  ggplot(aes(x = x, y = .resid)) +  
  geom_point() + facet_wrap(~xname, scales = "free") -> g
```

The plot

g



Comments

- ▶ There is serious curve in plot of residuals vs. fitted values. Suggests a transformation of y .
- ▶ The residuals-vs- x 's plots don't show any serious trends. Worst probably that potential curve against log-viscosity.
- ▶ Also, large positive residual, 10, that shows up on all plots. Perhaps transformation of y will help with this too.
- ▶ If residual-fitted plot OK, but some residual- x plots not, try transforming those x 's, eg. by adding x^2 to help with curve.

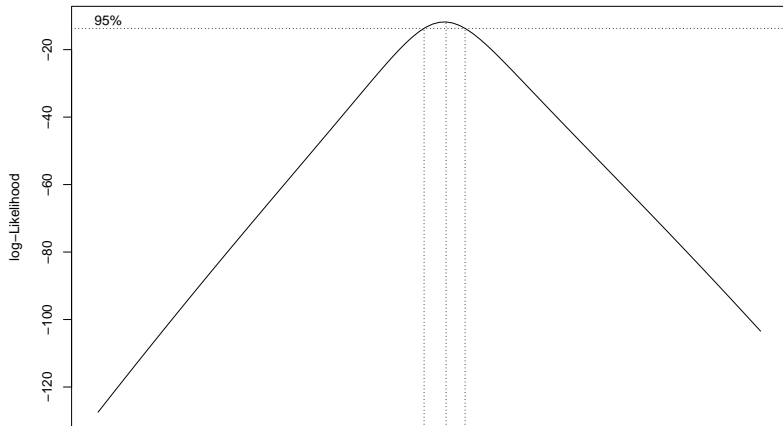
Which transformation?

- ▶ Best way: consult with person who brought you the data.
- ▶ Can't do that here!
- ▶ No idea what transformation would be good.
- ▶ Let data choose: "Box-Cox transformation".
- ▶ Scale is that of "ladder of powers": power transformation, but 0 is log.

Running Box-Cox

From package MASS:

```
boxcox(rut.depth ~ pct.a.surf + pct.a.base + fines + voids  
       log(viscosity) + run, data = asphalt)
```



Comments on Box-Cox plot

- ▶ λ represents power to transform y with.
- ▶ Best single choice of transformation parameter λ is peak of curve, close to 0.
- ▶ Vertical dotted lines give CI for λ , about $(-0.05, 0.2)$.
- ▶ $\lambda = 0$ means “log”.
- ▶ Narrowness of confidence interval mean that these not supported by data:
 - ▶ No transformation ($\lambda = 1$)
 - ▶ Square root ($\lambda = 0.5$)
 - ▶ Reciprocal ($\lambda = -1$).

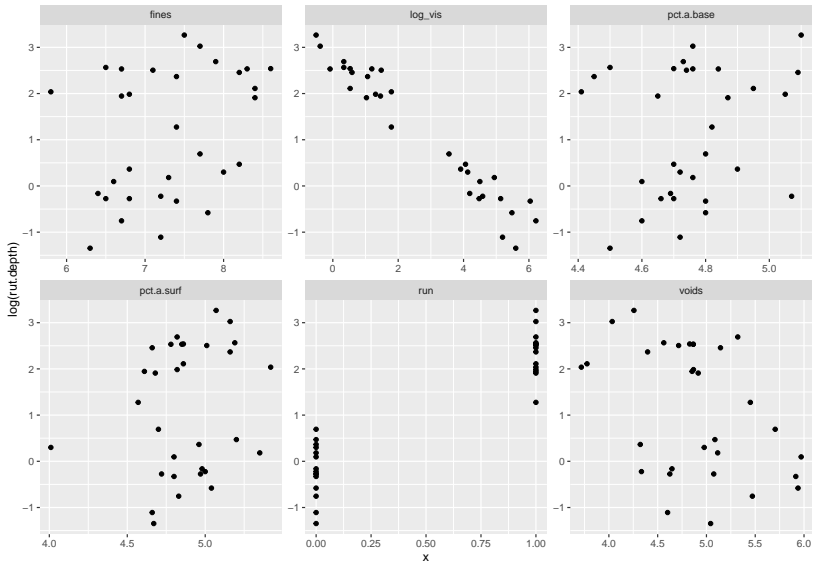
Relationships with explanatories

- ▶ As before: plot response (now `log(rut.depth)`) against other explanatory variables, all in one shot:

```
asphalt %>%  
  mutate(log_vis=log(viscosity)) %>%  
  pivot_longer(  
    c(pct.a.surf:voids, run, log_vis),  
    names_to="xname", values_to="x"  
  ) %>%  
  ggplot(aes(y = log(rut.depth), x = x)) + geom_point() +  
  facet_wrap(~xname, scales = "free") -> g3
```

The new plots

gg3



Modelling with transformed response

- ▶ These trends look pretty straight, especially with `log.viscosity`.
- ▶ Values of `log.rut.depth` for each run have same spread.
- ▶ Other trends weak, but are straight if they exist.
- ▶ Start modelling from the beginning again.
- ▶ Model `log.rut.depth` in terms of everything else, see what can be removed:

```
rut.2 <- lm(log(rut.depth) ~ pct.a.surf + pct.a.base +  
  fines + voids + log(viscosity) + run, data = asphalt)
```

- ▶ use `tidy` from `broom` to display just the coefficients.

Output

```
tidy(rut.2)
```

```
# A tibble: 7 x 5
```

	term <chr>	estimate <dbl>	std.error <dbl>	statistic <dbl>	p.value <dbl>
1	(Intercept)	-1.57	2.44	-0.646	0.525
2	pct.a.surf	0.584	0.232	2.52	0.0190
3	pct.a.base	-0.103	0.369	-0.280	0.782
4	finest	0.0978	0.0941	1.04	0.309
5	voids	0.199	0.123	1.62	0.119
6	log(viscosity)	-0.558	0.0854	-6.53	0.000000945
7	run	0.340	0.339	1.00	0.326

```
summary(rut.2)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + pct.a.base + fin
```

Taking out everything non-significant

► Try: remove everything but pct.a.surf and log.viscosity:

```
rut.3 <- lm(log(rut.depth) ~ pct.a.surf + log(viscosity), data = asphal  
summary(rut.3)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + log(viscosity), data = aspha
```

Residuals:

	Min	1Q	Median	3Q	Max
	-0.61938	-0.21361	0.06635	0.14932	0.63012

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.90014	1.08059	0.833	0.4119
pct.a.surf	0.39115	0.21879	1.788	0.0846 .
log(viscosity)	-0.61856	0.02713	-22.797	<2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3208 on 28 degrees of freedom

Find the largest P-value by eye:

```
tidy(rut.2)
```

```
# A tibble: 7 x 5
```

	term <chr>	estimate <dbl>	std.error <dbl>	statistic <dbl>	p.value <dbl>
1	(Intercept)	-1.57	2.44	-0.646	0.525
2	pct.a.surf	0.584	0.232	2.52	0.0190
3	pct.a.base	-0.103	0.369	-0.280	0.782
4	finest	0.0978	0.0941	1.04	0.309
5	voids	0.199	0.123	1.62	0.119
6	log(viscosity)	-0.558	0.0854	-6.53	0.000000945
7	run	0.340	0.339	1.00	0.326

```
summary(rut.2)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + pct.a.base + fin
```

Get the computer to find the largest P-value for you

► Output from tidy is itself a data frame, thus:

```
tidy(rut.2) %>% arrange(p.value)
```

```
# A tibble: 7 x 5
```

	term <chr>	estimate <dbl>	std.error <dbl>	statistic <dbl>	p.value <dbl>
1	log(viscosity)	-0.558	0.0854	-6.53	0.000000945
2	pct.a.surf	0.584	0.232	2.52	0.0190
3	voids	0.199	0.123	1.62	0.119
4	finest	0.0978	0.0941	1.04	0.309
5	run	0.340	0.339	1.00	0.326
6	(Intercept)	-1.57	2.44	-0.646	0.525
7	pct.a.base	-0.103	0.369	-0.280	0.782

► Largest P-value at the bottom.

Take out pct.a.base

- Copy and paste the lm code and remove what you're removing:

```
rut.4 <- lm(log(rut.depth) ~ pct.a.surf + fines + voids +  
            log(viscosity) + run, data = asphalt)  
summary(rut.4)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + fines + voids + log(v  
    run, data = asphalt)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.51610	-0.18785	-0.02248	0.18364	0.57160

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-2.07850	1.60665	-1.294	0.2076
pct.a.surf	0.59299	0.22526	2.632	0.0143 *
fines	0.08895	0.08701	1.022	0.3165

“Update”

Another way to do the same thing:

```
rut.4 <- update(rut.2, . ~ . - pct.a.base)
summary(rut.4)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + fines + voids +
    run, data = asphalt)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.51610	-0.18785	-0.02248	0.18364	0.57160

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-2.07850	1.60665	-1.294	0.2076
pct.a.surf	0.59299	0.22526	2.632	0.0143 *
fines	0.08805	0.08701	1.022	0.3165

Take out fines:

```
rut.5 <- update(rut.4, . ~ . - fines)
summary(rut.5)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + voids + log(viscosity) + run, data = asphalt)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.57275	-0.20080	0.01061	0.17711	0.59774

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	-1.25533	1.39147	-0.902	0.3753	
pct.a.surf	0.54837	0.22118	2.479	0.0200	*
voids	0.23188	0.11676	1.986	0.0577	.
log(viscosity)	-0.58039	0.07723	-7.516	5.59e-08	***

Take out run:

```
rut.6 <- update(rut.5, . ~ . - run)
summary(rut.6)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + voids + log(viscosity),
    data = asphalt)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.53548	-0.20181	-0.01702	0.16748	0.54707

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	-1.02079	1.36430	-0.748	0.4608	
pct.a.surf	0.55547	0.22044	2.520	0.0180	*
voids	0.24479	0.11560	2.118	0.0436	*
log(viscosity)	-0.64649	0.02879	-22.458	<2e-16	***

Comments

- ▶ Here we stop: `pct.a.surf`, `voids` and `log.viscosity` would all make fit significantly worse if removed. So they stay.
- ▶ Different final result from taking things out one at a time (top), than by taking out 4 at once (bottom):

```
summary(rut.6)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + voids + log(viscosity),  
    data = asphalt)
```

Residuals:

	Min	1Q	Median	3Q	Max
	-0.53548	-0.20181	-0.01702	0.16748	0.54707

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	1.00070	1.26420	0.792	0.4600

Comments on variable selection

- ▶ Best way to decide which x 's belong: expert knowledge: which of them should be important.
- ▶ Best automatic method: what we did, “backward selection”.
- ▶ Do not learn about “stepwise regression”! **eg. here**
- ▶ R has function `step` that does backward selection, like this:

```
step(rut.2, direction = "backward", test = "F")
```

Gets same answer as we did (by removing least significant x).

- ▶ Removing non-significant x 's may remove interesting ones whose P-values happened not to reach 0.05. Consider using less stringent cutoff like 0.20 or even bigger.
- ▶ Can also fit all possible regressions, as over (may need to do `install.packages("leaps")` first).

All possible regressions (output over)

Uses package leaps:

```
leaps <- regsubsets(log(rut.depth) ~ pct.a.surf +  
                    pct.a.base + fines + voids +  
                    log(viscosity) + run,  
                    data = asphalt, nbest = 2)  
s <- summary(leaps)  
with(s, data.frame(rsq, outmat)) -> d
```

The output

```
d %>% rownames_to_column("model") %>% arrange(desc(rsq))
```

		model	rsq	pct.a.surf	pct.a.base	finest	voids	log.viscosity.	run
1	6	(1)	0.9609642	*	*	*	*		* *
2	5	(1)	0.9608365	*		*	*		* *
3	5	(2)	0.9593265	*	*	*	*		* *
4	4	(1)	0.9591996	*			*		* *
5	4	(2)	0.9589206	*		*	*		*
6	3	(1)	0.9578631	*			*		*
7	3	(2)	0.9534561	*		*			*
8	2	(1)	0.9508647	*					*
9	2	(2)	0.9479541				*		*
10	1	(1)	0.9452562						*
11	1	(2)	0.8624107						*

Comments

- ▶ Problem: even adding a worthless x increases R-squared. So try for line where R-squared stops increasing “too much”, eg. top line (just `log.viscosity`), first 3-variable line (backwards-elimination model). Hard to judge.
- ▶ One solution (STAC67): adjusted R-squared, where adding worthless variable makes it go down.
- ▶ `data.frame` rather than `tibble` because there are several columns in `outmat`.

All possible regressions, adjusted R-squared

```
with(s, data.frame(adjr2, outmat)) %>%  
  rownames_to_column("model") %>%  
  arrange(desc(adjr2))
```

		model	adjr2	pct.a.surf	pct.a.base	fines	voids	log.viscosity.	run
1	3	(1)	0.9531812	*			*		*
2	5	(1)	0.9530038	*		*	*		* *
3	4	(1)	0.9529226	*			*		* *
4	4	(2)	0.9526007	*		*	*		*
5	6	(1)	0.9512052	*	*	*	*		* *
6	5	(2)	0.9511918	*	*	*	*		*
7	3	(2)	0.9482845	*		*			*
8	2	(1)	0.9473550	*					*
9	2	(2)	0.9442365				*		*
10	1	(1)	0.9433685						*
11	1	(2)	0.8576662						*

Revisiting the best model

► Best model was our rut.6:

```
tidy(rut.6)
```

```
# A tibble: 4 x 5
```

	term <chr>	estimate <dbl>	std.error <dbl>	statistic <dbl>	p.value <dbl>
1	(Intercept)	-1.02	1.36	-0.748	4.61e- 1
2	pct.a.surf	0.555	0.220	2.52	1.80e- 2
3	voids	0.245	0.116	2.12	4.36e- 2
4	log(viscosity)	-0.646	0.0288	-22.5	5.29e-19

```
summary(rut.6)
```

Call:

```
lm(formula = log(rut.depth) ~ pct.a.surf + voids + log(viscosity),  
    data = asphalt)
```

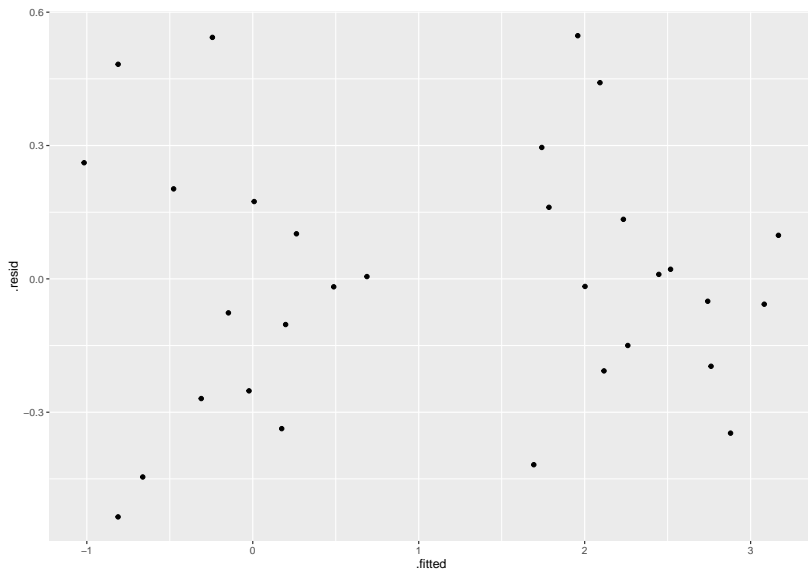
Revisiting (2)

- ▶ Regression slopes say that rut depth increases as log-viscosity decreases, pct.a.surf increases and voids increases. This more or less checks out with out scatterplots against log.viscosity.
- ▶ We should check residual plots again, though previous scatterplots say it's unlikely that there will be a problem:

```
g <- ggplot(rut.6, aes(y = .resid, x = .fitted)) +  
geom_point()
```

Residuals against fitted values

g



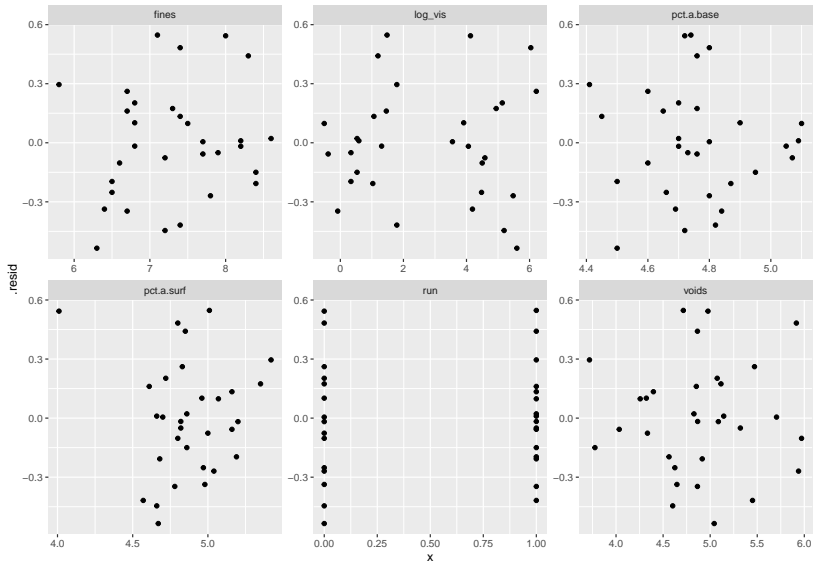
Plotting residuals against x's

- Do our trick again to put them all on one plot:

```
augment(rut.6, asphalt) %>%  
  mutate(log_vis=log(viscosity)) %>%  
  pivot_longer(  
    c(pct.a.surf:voids, run, log_vis),  
    names_to="xname", values_to="x",  
  ) %>%  
  ggplot(aes(y = .resid, x = x)) + geom_point() +  
  facet_wrap(~xname, scales = "free") -> g2
```

Residuals against the x's

g2



Comments

- ▶ None of the plots show any sort of pattern. The points all look random on each plot.
- ▶ On the plot of fitted values (and on the one of `log.viscosity`), the points seem to form a “left half” and a “right half” with a gap in the middle. This is not a concern.
- ▶ One of the `pct.a.surf` values is low outlier (4), shows up top left of that plot.
- ▶ Only two possible values of `run`; the points in each group look randomly scattered around 0, with equal spreads.
- ▶ Residuals seem to go above zero further than below, suggesting a mild non-normality, but not enough to be a problem.

Variable-selection strategies

- ▶ Expert knowledge.
- ▶ Backward elimination.
- ▶ All possible regressions.
- ▶ Taking a variety of models to experts and asking their opinion.
- ▶ Use a looser cutoff to eliminate variables in backward elimination (eg. only if P-value greater than 0.20).
- ▶ If goal is prediction, eliminating worthless variables less important.
- ▶ If goal is understanding, want to eliminate worthless variables where possible.
- ▶ Results of variable selection not always reproducible, so caution advised.