

Math 4MB3 Project Notebook 2018

Sang Woo Park (The Infective Collective)

April 1, 2018 @ 19:03

Friday 9 March 2018

Group Meeting

Approximate Duration: 0.5 Hours

- Decided on a project topic. We will be studying spatial synchrony.

Wednesday 14 March 2018

Group Meeting

Approximate Duration: 1 Hour

- Discussed what papers we should read; spent most of the class time reading over papers.
- We want to come up with a reasonable model by 19 March.

Thursday 15 March 2018

Solo work *Approximate Duration: 30 minutes*

- Literature review and brainstorming.

There are number of models we can use for this study. One of the simplest model that we can use is the one used by (Grenfell et al., 1995). We can slightly generalize their model to make it more like the logistic map we studied in class. Assuming identical population size of N across patches, we can write

$$\begin{aligned}\frac{dS_i}{dt} &= \mu(N - S_i) - \beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) S_i \\ \frac{dE_i}{dt} &= \beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) S_i - (\sigma + \mu) E_i \\ \frac{dI_i}{dt} &= \sigma E_i - (\gamma + \mu) I_i \\ \frac{dR_i}{dt} &= \gamma I_i - \mu R_i\end{aligned}$$

On the other hand (slightly tangential but relevant to the project), we can write a discrete time model under the tSIR framework (Finkenstädt and Grenfell, 2000; Becker and Grenfell, 2017) and we might be able to apply the analytical result presented in class.

$$S_{i,t+1} = B_{i,t} + S_{i,t} - I_{i,t+1}$$

$$E[I_{i,t+1}] = \beta_{t+1} S_{i,t} \sum_{j=1}^n m_{ij} I_{j,t}$$

tSIR model is supposed to be a tool to estimate transmission rate over time using a GLM framework but parameter estimation becomes more difficult when we add spatial structures. Instead, we can try to use estimated transmission rates and compare how synchrony and coherence might vary. This is something I might do for my own interest when I have some extra time...

Friday 16 March 2018

Group work *Approximate Duration: 1 hour*

- Discussed different model structures
- We want to consider a discrete time model due to its simplicity
- Discussed various ways of discretizing the model

Saturday 17 March 2018

Solo work *Approximate Duration: 1.5 hours*

Consider an SIR model with spatial structure:

$$\frac{dS_i}{dt} = \mu(N - S_i) - \beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) S_i$$

$$\frac{dI_i}{dt} = \beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) S_i - (\gamma + \mu) I_i$$

$$\frac{dR_i}{dt} = \gamma I_i - \mu R_i$$

We want to discretize this model in a biologically sensible way. In the absence of natural birth, dynamics of the susceptible population can be described by

$$\frac{dS_i}{dt} = - \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) S_i$$

Then, $\left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j\right) + \mu\right)$ can be thought of as per capita "death rate". Then, it follows that

$$\begin{aligned}
\frac{dS_i}{dt} &= - \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) S_i \\
\Rightarrow \frac{1}{S_i} \frac{dS_i}{dt} &= - \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) \\
\Rightarrow \int_t^{t+\Delta t} \frac{d \log S_i}{dt} dt &= - \int_t^{t+\Delta t} \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) dt \\
\Rightarrow \log (S_i(t + \Delta t) / S_i(t)) &= - \int_t^{t+\Delta t} \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) dt \\
\Rightarrow S_i(t + \Delta t) &= \exp \left(- \int_t^{t+\Delta t} \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) dt \right) S_i(t)
\end{aligned}$$

where

$$\exp \left(- \int_t^{t+\Delta t} \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) dt \right)$$

represents survival probability of a susceptible individual between time t and $t + \Delta t$. Assuming that Δt is sufficiently small, we have

$$- \int_t^{t+\Delta t} \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) dt \approx \left(\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu \right) \Delta t$$

By applying this approximation, we are essentially assuming that $I_j(t)$ does not vary much between t and $t + \Delta t$. We can do a second order approximation here to account for changes in $I_j(t)$ over Δ but we don't have to worry about that yet (He et al., 2009). Then, it follows that

$$S_i(t + \Delta t) = S_i(t) - \left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t)$$

It is convenient to express it this way because

$$\left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t)$$

represents the number of people that leave the susceptible compartment and incidence (number of people infected between time t and $t + \Delta t$) can be approximated by

$$i_i(t) = \frac{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right)}{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu} \left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t)$$

where $i_i(t)$ denotes incidence. i_i is a really terrible notation and I should come up with something better... Note that

$$\frac{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right)}{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu}$$

is approximately equal to the probability that a infection occurs before a susceptible individual dies from natural mortality. Likewise, we can do similar analysis and derive survival probability of an infected individual between time t and $t + \Delta t$:

$$\exp(-(\gamma + \mu)\Delta t)$$

In this case, this is exact (not an approximation) because "death rate" does not vary over time. Hence, we have

$$I_i(t + \Delta t) = I(t) + i_i(t) - (1 - e^{-(\gamma + \mu)\Delta t}) I(t)$$

we denote number of recovered individuals between t and $t + \Delta t$ by $r(t)$:

$$r_i(t) = \frac{\gamma}{\gamma + \mu} (1 - e^{-(\gamma + \mu)\Delta t}) I(t)$$

Then, by similar argument

$$R_i(t + \Delta t) = R_i(t) + r_i(t) - (1 - e^{-\mu\Delta t}) R_i$$

Then, the entire model is given by

$$\begin{aligned} S_i(t + \Delta t) &= S_i(t) + b_i(t) - \left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t) \\ I_i(t + \Delta t) &= I(t) + i_i(t) - (1 - e^{-(\gamma + \mu)\Delta t}) I(t) \\ R_i(t + \Delta t) &= R_i(t) + r_i(t) - (1 - e^{-\mu\Delta t}) R_i \end{aligned}$$

where

$$\begin{aligned} b_i(t) &= \mu N \Delta t \\ i_i(t) &= \frac{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right)}{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu} \left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t) \\ r_i(t) &= \frac{\gamma}{\gamma + \mu} (1 - e^{-(\gamma + \mu)\Delta t}) I(t) \end{aligned}$$

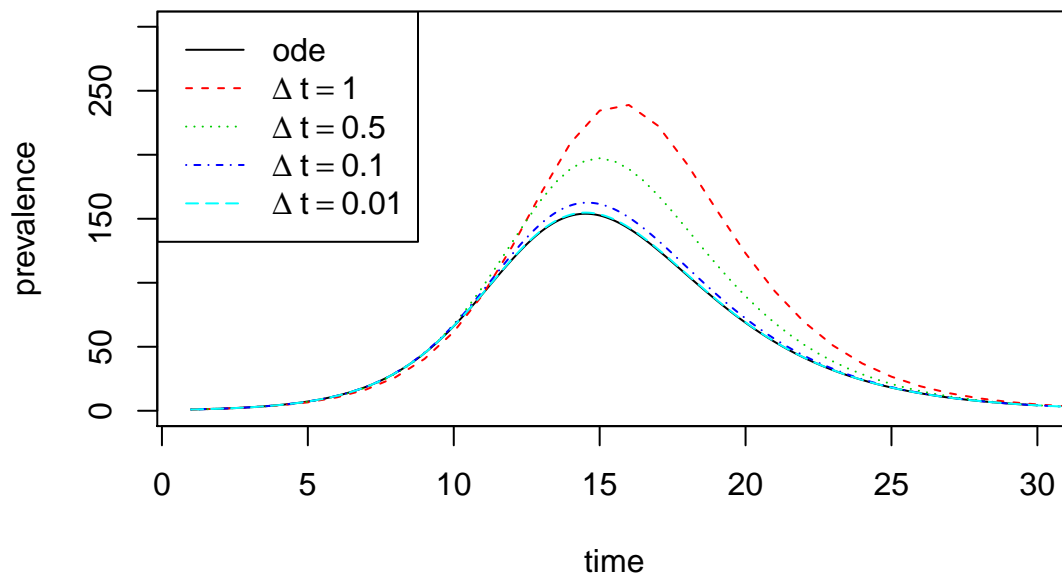
This doesn't exactly keep the population size constant and if we wanted to keep the population size constant, we would let

$$b_i(t) = \frac{\mu}{\beta(t) \left(\sum_{j=1}^n m_{ij} I_j \right) + \mu} \left(1 - e^{-(\beta(t)(\sum_{j=1}^n m_{ij} I_j) + \mu)\Delta t} \right) S_i(t) + \frac{\mu}{\gamma + \mu} (1 - e^{-(\gamma + \mu)\Delta t}) I(t)$$

Since we have a nice probabilistic interpretation of the model, we can add stochasticity by adding appropriate binomial and multinomial random variables (beta binomial and dirichlet

multinomial for overdispersion in process error (Li et al., 2017) but we probably don't need to worry about this).

We can compare how different this model is from ODE through simulations. First, we can start with a simple SIR case without birth terms.



Note that our purpose is not necessarily to approximate the ode but to come up with a biologically reasonable discrete time model. It's worth keeping in mind that choices of Δt matters if it is too large with respect to disease time scale but otherwise, we don't have to make it too small. We will still obtain qualitatively similar dynamics (but what happens when we include seasonal forcing?).

Monday 19 March 2018

Group Meeting

Approximate Duration: 1 Hour

- Discussed model further
- Discussed how we can implement stochastic model
- Divided up the work

Tuesday 20 March 2018

Solo work

Approximate Duration: 4 Hours

- Spent two hours trying to get an analytical handle on the model and got nowhere near.
- The following notes are my second attempt to get somewhere (hopefully).

Let's try to start with a simpler case. Hopefully, we can get more insight later on. Consider a coupled SI model. Assume that mixing matrix is given by

$$M = \begin{bmatrix} 1 - m_1 & m_2 \\ m_1 & 1 - m_2 \end{bmatrix}$$

For sake of simplicity, assume $m_1 = m_2 = 1/2$. Then, it follows that

$$\begin{aligned} S_i(t + \Delta t) &= S_i(t) + (1 - e^{-\gamma\Delta t}) I_i(t) - (1 - e^{-\beta(t)(I_1+I_2)\Delta t/2}) S_i(t) \\ I_i(t + \Delta t) &= I_i(t) + (1 - e^{-\beta(t)(I_1+I_2)\Delta t/2}) S_i(t) - (1 - e^{-\gamma\Delta t}) I_i(t) \end{aligned}$$

Then, it follows that

$$\begin{aligned} S'_2 - S'_1 &= e^{-\beta(t)(I_1+I_2)\Delta t/2} (S_2 - S_1) + (1 - e^{-\gamma\Delta t}) (I_2 - I_1) \\ I'_2 - I'_1 &= e^{-\gamma\Delta t} (I_2 - I_1) + (1 - e^{-\beta(t)(I_1+I_2)\Delta t/2}) (S_2 - S_1) \end{aligned}$$

Note that

$$S_2 - S_1 = (N - I_2) - (N - I_1) = I_1 - I_2$$

Then,

$$\begin{aligned} I'_2 - I'_1 &= e^{-\gamma\Delta t} (I_2 - I_1) - (1 - e^{-\beta(t)(I_1+I_2)\Delta t/2}) (I_2 - I_1) \\ &= (e^{-\gamma\Delta t} + e^{-\beta(t)(I_1+I_2)\Delta t/2} - 1) (I_2 - I_1) \\ S'_2 - S'_1 &= e^{-\beta(t)(I_1+I_2)\Delta t/2} (S_2 - S_1) - (1 - e^{-\gamma\Delta t}) (S_2 - S_1) \\ &= (e^{-\gamma\Delta t} + e^{-\beta(t)(I_1+I_2)\Delta t/2} - 1) (S_2 - S_1) \end{aligned}$$

So it seems that

$$e^{-\gamma\Delta t} + e^{-\beta(t)(I_1+I_2)\Delta t/2} - 1$$

could be the quantity that determines synchrony and coherence. Suppose that Δt is sufficiently small. Then, it follows that

$$\begin{aligned} e^{-\gamma\Delta t} + e^{-\beta(t)(I_1+I_2)\Delta t/2} - 1 &\approx 1 - \gamma\Delta t + 1 - \beta(t)(I_1 + I_2)\Delta t/2 - 1 \\ &= 1 - \gamma\Delta t - \beta(t)(I_1 + I_2)\Delta t/2 \end{aligned}$$

It seems to me that this quantity would be less than 1 but greater than 0 if Δt is small? Then, I think we obtain coherence.

It might be easier to work with a continuous time model for analytical results. Consider the following coupled SIS model:

$$\begin{aligned} \frac{dS_1}{dt} &= \gamma I_1 - \beta(t) ((1 - m_1)I_1 + m_2 I_2) S_1 \\ \frac{dS_2}{dt} &= \gamma I_2 - \beta(t) (m_1 I_1 + (1 - m_2)I_2) S_2 \\ \frac{dI_1}{dt} &= \beta(t) ((1 - m_1)I_1 + m_2 I_2) S_1 - \gamma I_1 \\ \frac{dI_2}{dt} &= \beta(t) (m_1 I_1 + (1 - m_2)I_2) S_2 - \gamma I_2 \end{aligned}$$

Then, necessary condition is that

$$\frac{dI_1}{dt} - \frac{dI_2}{dt} \rightarrow 0.$$

Note that

$$\begin{aligned} \frac{dI_1}{dt} - \frac{dI_2}{dt} &= \beta(t) ((1 - m_1)I_1 + m_2I_2) S_1 - \beta(t) (m_1I_1 + (1 - m_2)I_2) S_2 - \gamma(I_1 - I_2) \\ &= \beta(t) (((1 - m_1)I_1 + m_2I_2)(1 - I_1) - (m_1I_1 + (1 - m_2)I_2)(1 - I_2)) - \gamma(I_1 - I_2) \\ &= \beta(t) ((I_1 - m_1I_1 + m_2I_2)(1 - I_1) - (m_1I_1 + I_2 - m_2I_2)(1 - I_2)) - \gamma(I_1 - I_2) \\ &= \beta(t) ((1 - 2m_1)I_1 + (m_1 - 1)I_1^2 - (1 - 2m_2)I_2 - (m_2 - 1)I_2^2) - \gamma(I_1 - I_2) \end{aligned}$$

Again, when $m_1 = m_2 = 1/2$, we have

$$\begin{aligned} &\beta(t) ((1 - 2m_1)I_1 + (m_1 - 1)I_1^2 - (1 - 2m_2)I_2 - (m_2 - 1)I_2^2) - \gamma(I_1 - I_2) \\ &= -\beta(t)(I_1^2 - I_2^2)/2 - \gamma(I_1 - I_2) \\ &= (-\beta(t)(I_1 + I_2)/2 - \gamma)(I_1 - I_2) \end{aligned}$$

Hence,

$$-\max \beta(t) - \gamma < \frac{d \log(I_1 - I_2)}{dt} = -\beta(t)(I_1 + I_2)/2 - \gamma < -\gamma$$

Therefore, it must become coherent as $\log(I_1 - I_2) \rightarrow -\infty$. When $m_1 = m_2 = m$,

$$\begin{aligned} &\beta(t) ((1 - 2m_1)I_1 + (m_1 - 1)I_1^2 - (1 - 2m_2)I_2 - (m_2 - 1)I_2^2) - \gamma(I_1 - I_2) \\ &= \beta(t) ((1 - 2m)(I_1 - I_2) + (m - 1)(I_1^2 - I_2^2)) - \gamma(I_1 - I_2) \\ &= (\beta(t)(1 - 2m + (m - 1)(I_1 + I_2)) - \gamma)(I_1 - I_2) \end{aligned}$$

Hence,

$$\frac{d \log(I_1 - I_2)}{dt} = (\beta(t)(1 - 2m + (m - 1)(I_1 + I_2)) - \gamma)$$

Note that

$$\beta(t)(1 - 2m + (m - 1)(I_1 + I_2)) - \gamma = \beta(t)(1 - 2m) - \beta(t)(1 - m)(I_1 + I_2) - \gamma < \beta(t)(1 - 2m) - \gamma$$

Then, when $\beta(t)(1 - 2m) - \gamma < 0$, this system *can* be coherent.

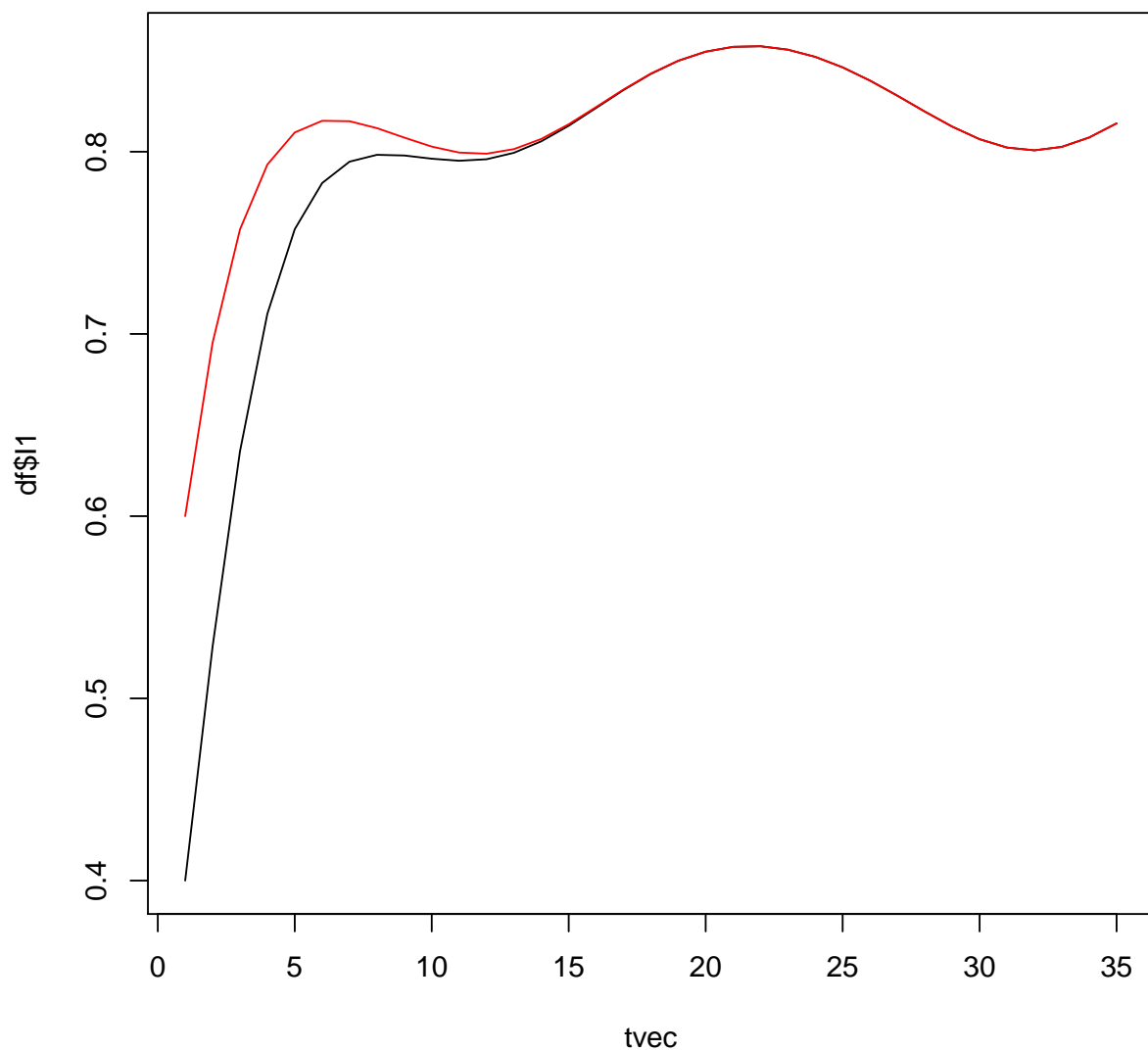
```
SI.grad <- function(t, y, par) {
  with(as.list(c(y, par)), {
    beta <- b0 * (1 + b1 * cos (2 * pi * t/period))

    dI1 <- beta * ((1 - m) * I1 + m * I2) * (1 - I1) - gamma * I1
    dI2 <- beta * (m * I1 + (1-m) * I2) * (1 - I2) - gamma * I2
    list(c(dI1, dI2))
  })
}
```

```
SI.par <- c(b0=0.6, b1=0.2, gamma=0.1, m = 0.001, period=20)
y <- c(I1=0.4, I2=0.6)
tvec <- seq(from=1, to=35, by=1)

df <- as.data.frame(ode(y, tvec, SI.grad, SI.par))

plot(tvec, df$I1, type="l")
lines(tvec, df$I2, col=2)
```



I think seasonal forcing is too strong in this case...??? We get dynamics that are not interesting at all. However, I think we can use this method as a stepping stone to try to tackle more sophisticated models.

Now, let's think about the big model instead of SIS

```
SIR.grad <- function(t, y, par) {
  with(as.list(c(y, par)), {
    beta <- b0 * (1 + b1 * cos (2 * pi * t/period))

    inf1 <- beta * ((1 - m) * I1 + m * I2) * S1

    dS1 <- mu * (1 - S1) - inf1
    dI1 <- inf1 - (gamma + mu) * I1
    dR1 <- gamma * I1 - mu * R1

    inf2 <- beta * (m * I1 + (1-m) * I2) * S2

    dS2 <- mu * (1 - S2) - inf2
    dI2 <- inf2 - (gamma + mu) * I2
    dR2 <- gamma * I2 - mu * R2

    Q <- beta * (1 - 2 * m - (1-m) * (I1 + I2)) - gamma

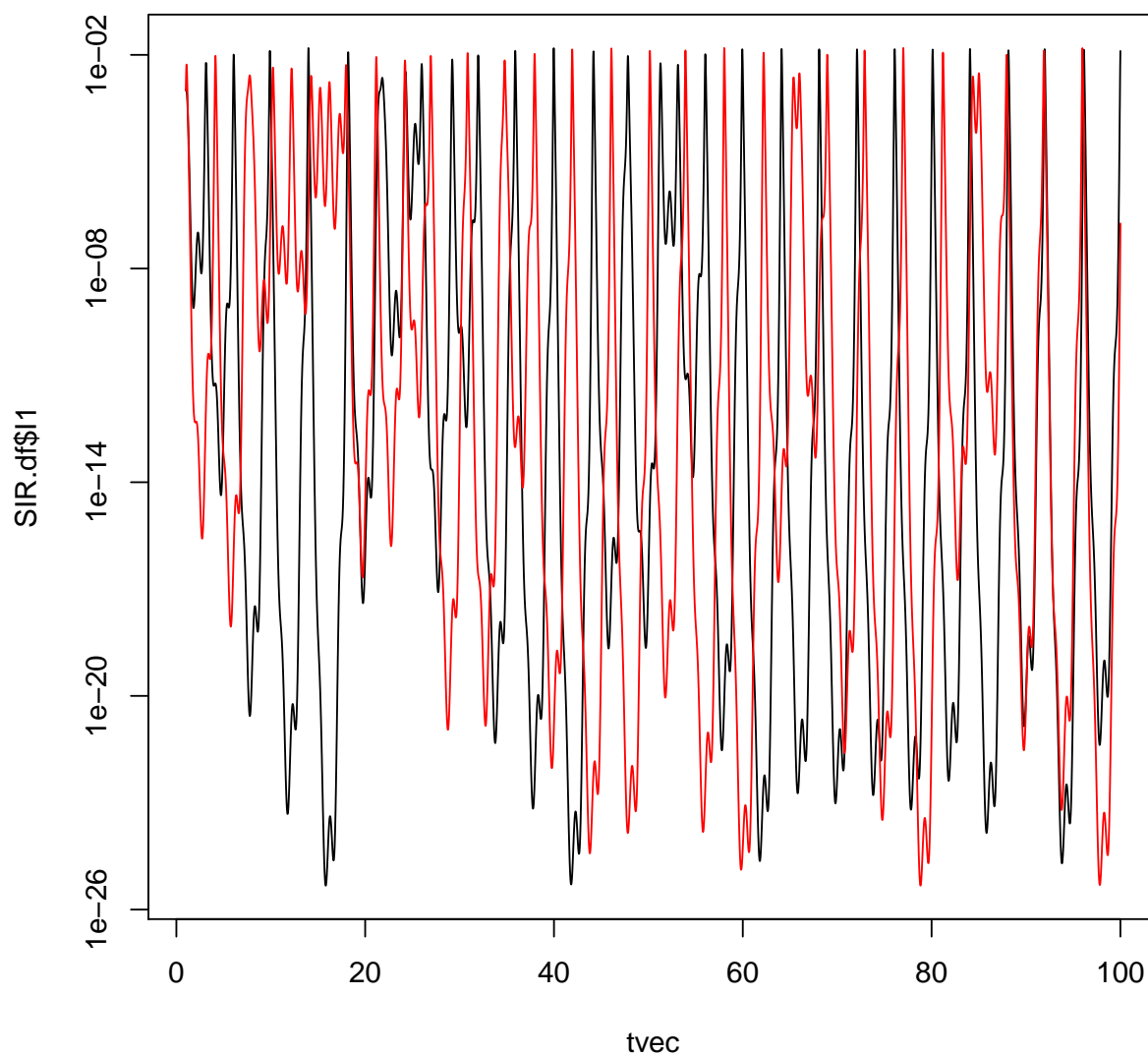
    list(c(dS1, dI1, dR1, dS2, dI2, dR2), Q=Q)
  })
}

## parameters taken from Earn et al

SIR.par <- c(b0=17*365/5, b1=0.25, gamma=365/5, m = 0, mu = 0.02, period=1)
y <- c(S1=0.05, I1=0.001, R1=1-0.05-0.001, S2=0.07, I2=0.001, R2=1-0.07-0.001)
tvec <- seq(from=1, to=100, by=1/365)

SIR.df <- as.data.frame(rk(y, tvec, SIR.grad, SIR.par))

plot(tvec, SIR.df$I1, type="l", log='y')
lines(tvec, SIR.df$I2, col=2)
```



Wednesday 21 March 2018

Group work

Approximate Duration: 1 Hour

- debugging code; further discussion on how to approach analytical results.

Thursday 22 March 2018

Solo work

Approximate Duration: 3 Hour

- worked a bit more on analytical stuff but didn't get far
- Instead, I made a bifurcation diagram

Let's try to work on the SI model a little more. I'm wondering if we get any interesting dynamics in the discrete case.

Assuming discrete time steps and equal coupling, the model would reduce down to

$$I_1(t + \Delta t) = I_1(t) + (1 - e^{-\beta(t)((1-m)I_1 + mI_2)\Delta t})(N - I_1) + (1 - e^{-\gamma\Delta t})I_1(t)$$

$$I_2(t + \Delta t) = I_2(t) + (1 - e^{-\beta(t)(mI_1 + (1-m)I_2)\Delta t})(N - I_2) + (1 - e^{-\gamma\Delta t})I_2(t)$$

I'm curious whether

$$\beta(t)(1 - 2m) - \gamma < 0$$

condition is any helpful here.

```
SI.discrete <- function(dt, t.step, y, param) {
  with(as.list(param), {
    I1 <- rep(NA, t.step+1)
    I2 <- rep(NA, t.step+1)

    I1[1] <- y[1]
    I2[1] <- y[2]

    quantity <- rep(NA, t.step+1)

    for (i in 1:t.step) {
      t <- i * dt

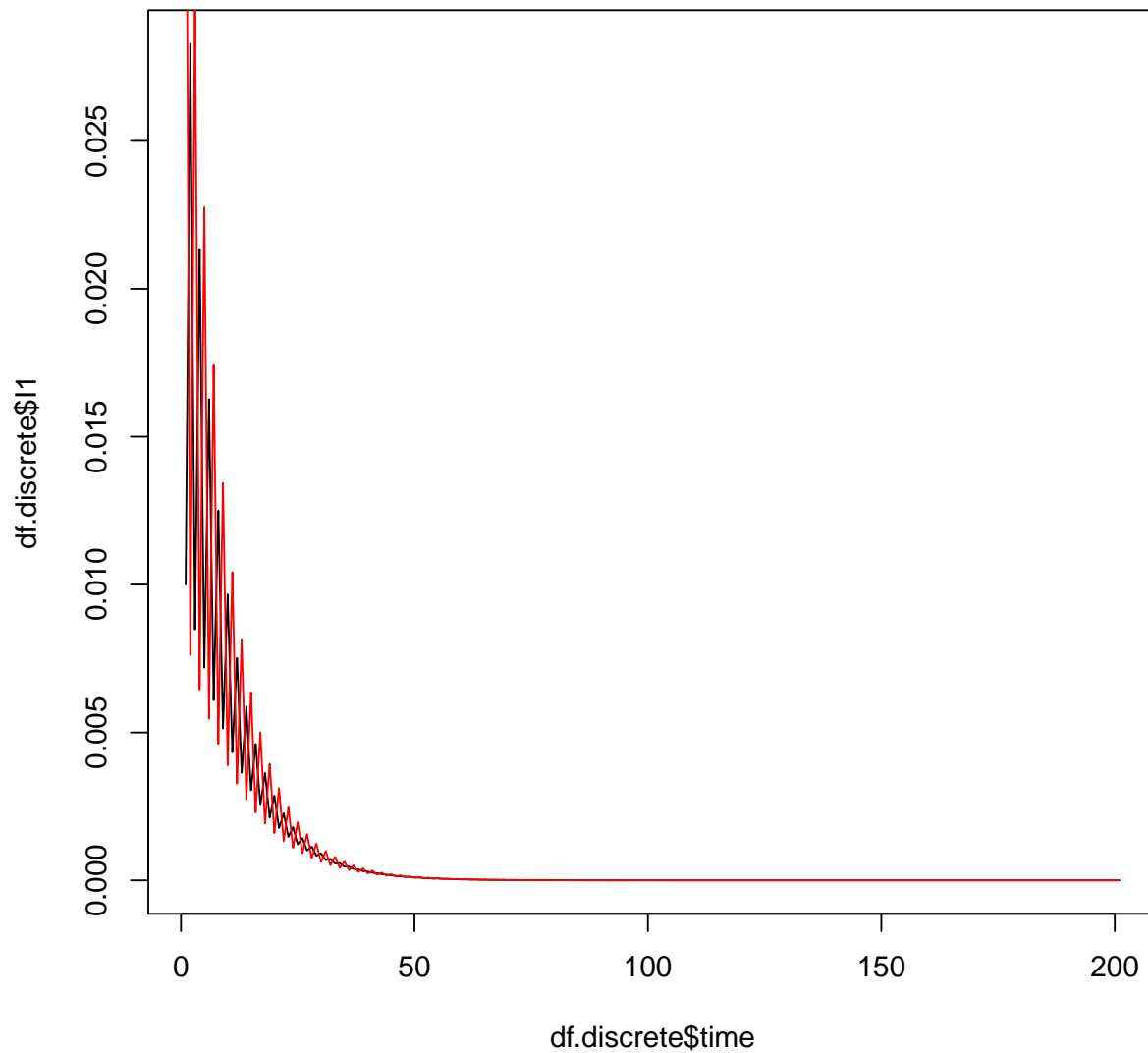
      beta <- b0 * (1 + b1 * cos (2 * pi * t/period))
      I1[i+1] <- I1[i] + (1 - exp(-beta * ((1-m) * I1[i] + m * I2[i]) * dt)) * (1 - I1[i])
      I2[i+1] <- I2[i] + (1 - exp(-beta * (m * I1[i] + (1-m) * I2[i]) * dt)) * (1 - I2[i])
      quantity[i+1] <- beta * (1 - 2 * m + (m-1) * (I1[i] + I2[i])) - gamma
    }

    data.frame(
      time=1:(t.step+1)*dt,
      I1=I1,
      I2=I2,
      quantity=quantity
    )
  })
}

SI.par <- c(b0=0.9, b1=0.2, gamma=4, m=1, period=2)
```

```
df.discrete <- SI.discrete(1, 200, c(0.01, 0.04), SI.par)

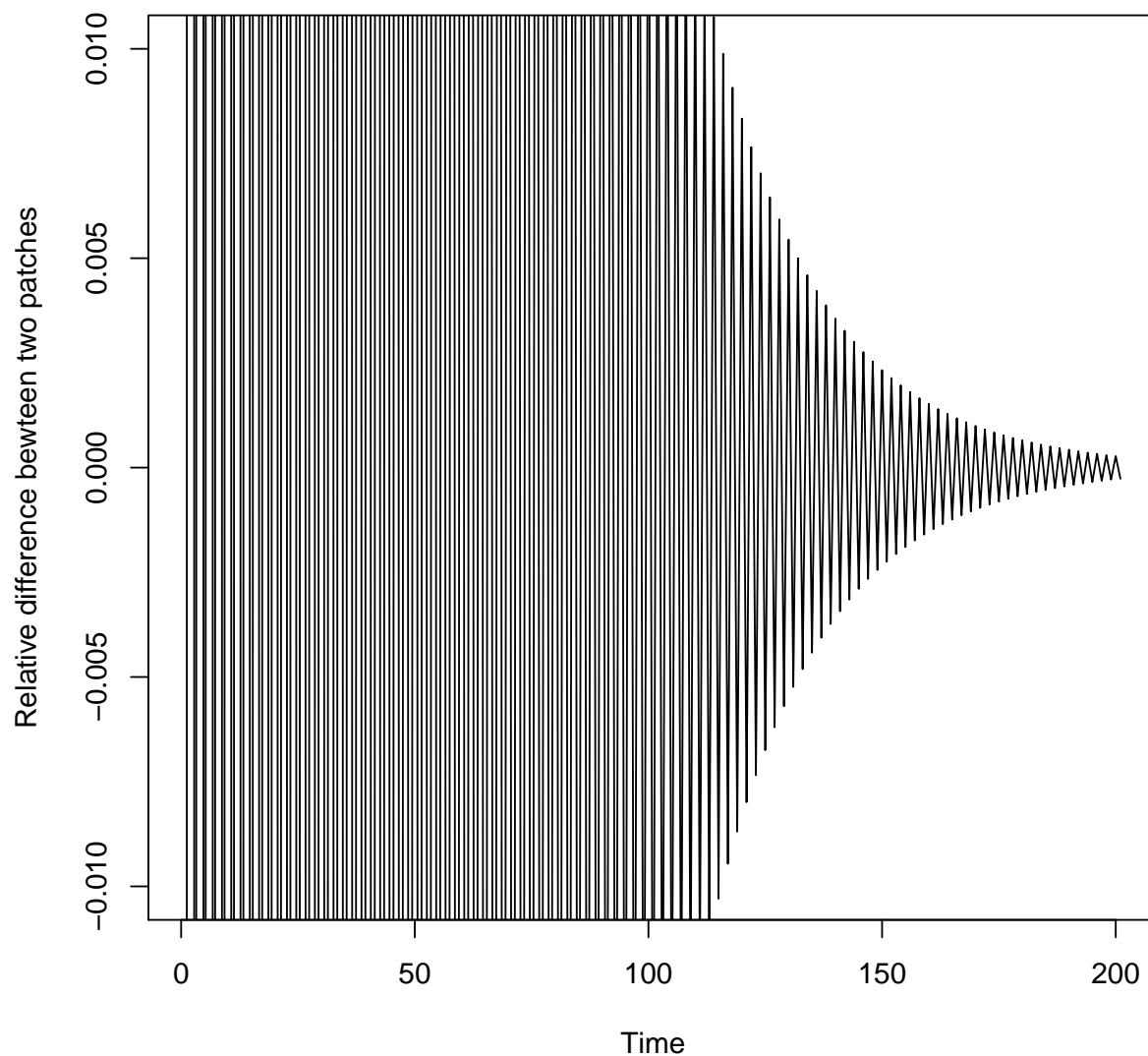
plot(df.discrete$time, df.discrete$I1, col=1, type="l")
lines(df.discrete$time, df.discrete$I2, col=2, type="l")
```



I tried out some values and it seems like we can't really get interesting dynamics in this case?? With these parameters, we get something interesting but they seem to become coherent eventually.

```
plot((df.discrete$I1 - df.discrete$I2)/df.discrete$I2,
     type="l",
     ylim=c(-1e-2, 1e-2),
```

```
ylab="Relative difference bewteen two patches",
xlab="Time")
```

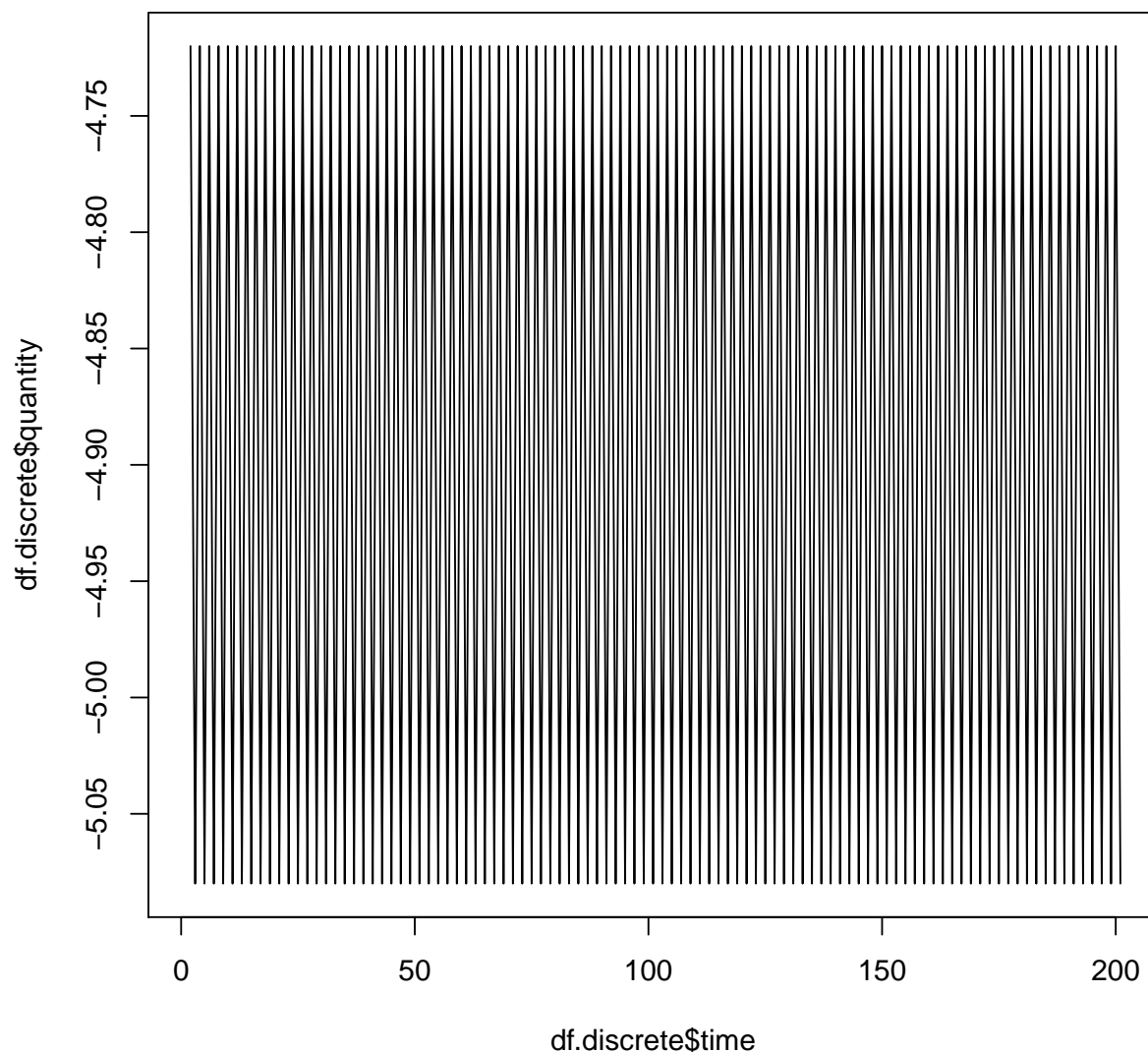


Our “true” quantity of interest was actually this (we’re going to call this $Q(t)$):

$$Q(t) = \beta(t)(1 - 2m - (1 - m)(I_1 + I_2)) - \gamma$$

How does this change over time?

```
plot(df.discrete$time, df.discrete$quantity, type="l")
```



It happens so that this quantity is always negative. This explains coherence!!

OK so is it possible to make this quantity positive? When $m = 1$, we have

$$Q(t) = -\beta(t) - \gamma < 0.$$

So I should have expected coherence...

I tried checking this value for the measles model but I don't think it really helps...

Thursday 15 March 2018

Solo work

Approximate Duration: 1.5 Hour

- Writing methods

Monday 26 March 2018

Group work

Approximate Duration: 1 Hour

- Discussing direction
- Abandon analytical work for now

Solo work

Approximate Duration: 2.5 Hour

- Organizing code
- Wrote a general purpose code that everyone can use for their parts so that we don't have to create several copies (SIRmodelnpatch.cpp).
- Working on stochastic model and bifurcation diagrams

Group work

Approximate Duration: 1 Hour

- Planning draft
- Explained how to use the general purpose code

Tuesday 27 March 2018

Solo work

Approximate Duration: 1 Hour

- Reviewing literature and deciding what figures I want to make

Group work

Approximate Duration: 1 Hour

- Fixing bugs on code
- We need to choose good initial conditions to get asynchronous behaviour.

Solo work

Approximate Duration: 6 Hour

- Coding, writing, editing and making figures
- Worked mostly on methods and stochastic

Friday 30 March 2018

Solo work

Approximate Duration: 2 Hour

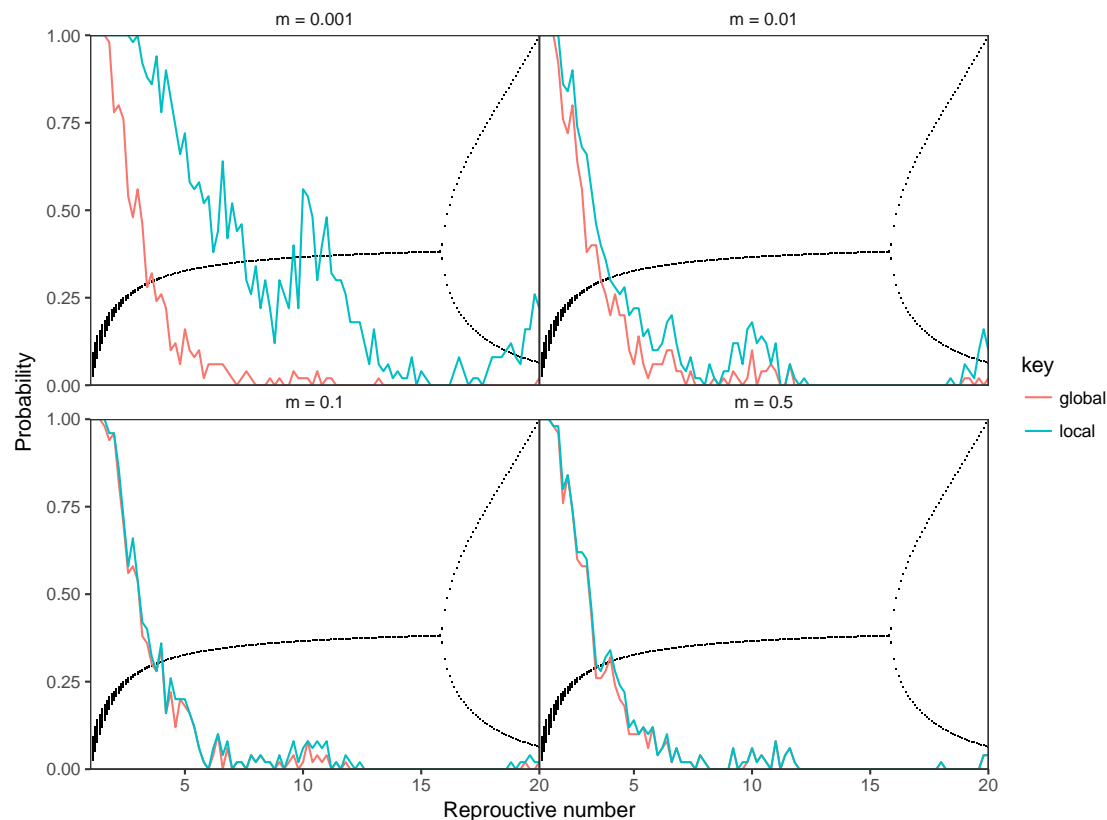
- Writing/testing code to produce R_0 v.s. local/global extinction probability figure
- Uploaded the code to collywobbles and it's running

Saturday 31 March 2018

Solo work

Approximate Duration: 1 Hour

I made a preliminary figure:



Realized that there is not much going on. I need to increase R_0 range and/or switch to term-time forcing.

Approximate Duration: 1 Hour

- Further exploring different parameter regions and term time.
- Switching to term time forcing and writing a big bifurcation file so that everyone can use.
- Fix stochastic.R code and rerun on collywobbles

Approximate Duration: 30 minutes

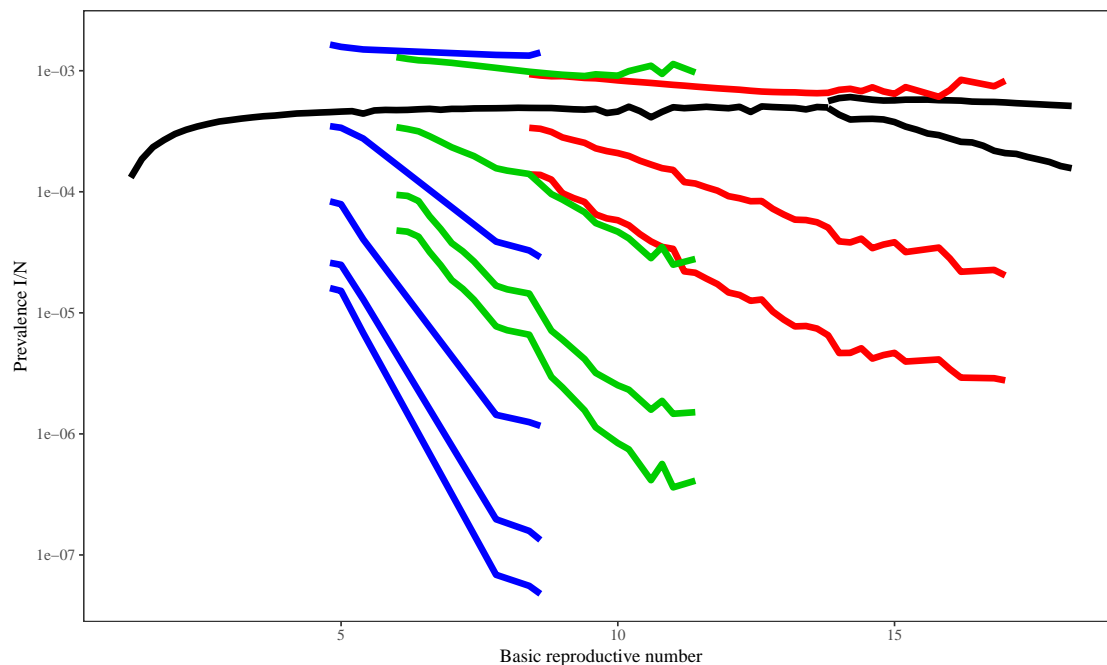
Bifurcation diagram looks crap. I tried to diagnose what's going on and tried to write down a more efficient ways to sample initial point (via Latin Hypercube Sample). I'm allowing it to run longer time so that I can remove transient dynamics for sure (hopefully).

Sunday 1 April 2018

Solo work

Approximate Duration: 1 Hour

Worked on a preliminary (?) bifurcation diagram:



Total time spent on this project

Group work: 7.5 hours

Solo work: 28.5 hours

References

- Becker, A. D. and B. T. Grenfell (2017). tsir: An r package for time-series susceptible-infected-recovered models of epidemics. *PloS one* 12(9), e0185528.
- Finkenstädt, B. F. and B. T. Grenfell (2000). Time series modelling of childhood diseases: a dynamical systems approach. *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 49(2), 187–205.

- Grenfell, B., B. Bolker, and A. Kleczkowski (1995). Seasonality and extinction in chaotic metapopulations. *Proc. R. Soc. Lond. B* 259(1354), 97–103.
- He, D., E. L. Ionides, and A. A. King (2009). Plug-and-play inference for disease dynamics: measles in large and small populations as a case study. *Journal of the Royal Society Interface*.
- Li, M., J. Dushoff, and B. M. Bolker (2017). Fitting mechanistic epidemic models to data: a comparison of simple markov chain monte carlo approaches. *bioRxiv*, 110767.