Extension to conditional SMC

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We now consider extending the results of **?** to the case of conditional SMC. In particular, the SMC updates will be conditioned on a particular trajectory surviving. We concentrate on the exchangeable model, so we may take WLOG that the "immortal line" is the trajectory containing individual 1 from each generation. We first assume the simplest case, with multinomial resampling; analogous to the standard SMC case where

$$v_t^{(i)} \overset{d}{=} \mathrm{Bin}(N, w_t^{(i)}), \qquad i = 1, \dots, N$$

yielding the coalescence rate

$$c_N(t) := \frac{1}{(N)_2} \sum_{i=1}^{N} \mathbb{E}\left[(v_t^{(i)})_2\right] = \sum_{i=1}^{N} (w_t^{(i)})^2. \tag{1}$$

But now, since the first line is immortal, in each time step the first individual must have at least one offspring. The remaining $N-1$ offspring are assigned multinomially to the N possible parents as usual, giving the offspring numbers:

$$\begin{aligned}
\tilde{v}_t^{(1)} &\overset{d}{=} 1 + \mathrm{Bin}(N-1, w_t^{(1)}) \\
\tilde{v}_t^{(i)} &\overset{d}{=} \mathrm{Bin}(N-1, w_t^{(i)}), \qquad i = 2, \dots, N.
\end{aligned}$$

We therefore have the following moments:

$$\begin{aligned}
&\mathbb{E}(\tilde{v}_t^{(i)}) = (N-1)w_t^{(i)} && \mathrm{Var}(\tilde{v}_t^{(i)}) = (N-1)w_t^{(i)}(1-w_t^{(i)}) \qquad i = 2, \dots, N \\
&\mathbb{E}(\tilde{v}_t^{(1)}) = (N-1)w_t^{(1)} + 1 && \mathrm{Var}(\tilde{v}_t^{(1)}) = (N-1)w_t^{(1)}(1-w_t^{(1)})
\end{aligned}$$

and we can derive the altered coalescence rate:

$$\begin{aligned}
\tilde{c}_N(t) &= \frac{1}{(N)_2} \sum_{i=1}^{N} \mathbb{E}\left[(\tilde{v}_t^{(i)})_2\right] \\
&= \frac{1}{(N)_2} \mathbb{E}\left[(\tilde{v}_t^{(1)})^2 - \tilde{v}_t^{(1)}\right] + \frac{1}{(N)_2} \sum_{i=2}^{N} \mathbb{E}\left[(\tilde{v}_t^{(i)})^2 - \tilde{v}_t^{(i)}\right] \\
&= \frac{1}{(N)_2} \sum_{i=2}^{N} (N-1)(N-2)(w_t^{(i)})^2 + (N^2 - 3N + 2)(w_t^{(1)})^2 + 2(N-1)w_t^{(1)} \\
&= \frac{1}{(N)_2} \sum_{i=1}^{N} (N-1)(N-2)(w_t^{(i)})^2 + 2(N-1)w_t^{(1)} \\
&= \frac{N-2}{N} c_N(t) + \frac{2}{N} w_t^{(1)}
\end{aligned} \tag{2}$$