Terrorists never congregate in even numbers[1]

Andreas E. Kyprianou, University of Bath, UK.

[1] Joint work with Steven Pagett, Tim Rogers

Terrorists, consensus and biological clustering

- Consider a collection of n identical particles (terrorists/opinions), grouped together into some number of clusters (cells/consensus). We define a stochastic dynamical process as follows:
- Every k-tuple of clusters coalesces at rate $\alpha(k)n^{1-k}$, independently of everything else that happens in the system. The coalescing cells are merged to form a single cluster with size equal to the sum of the sizes of the merged clusters.
- Clusters fragment (terrorist cells are dispersed/consensus breaks) at constant rate $\lambda > 0$, independently of everything else that happens in the system. Fragmentation of a cluster of size ℓ results in ℓ 'singleton' clusters of size one.

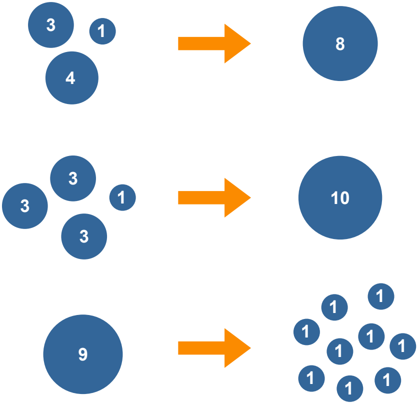
Terrorists, consensus and biological clustering

- Consider a collection of n identical particles (terrorists/opinions), grouped together into some number of clusters (cells/consensus). We define a stochastic dynamical process as follows:
- Every k-tuple of clusters coalesces at rate $\alpha(k)n^{1-k}$, independently of everything else that happens in the system. The coalescing cells are merged to form a single cluster with size equal to the sum of the sizes of the merged clusters.
- Clusters fragment (terrorist cells are dispersed/consensus breaks) at constant rate $\lambda > 0$, independently of everything else that happens in the system. Fragmentation of a cluster of size ℓ results in ℓ 'singleton' clusters of size one.

Terrorists, consensus and biological clustering

- Consider a collection of n identical particles (terrorists/opinions), grouped together into some number of clusters (cells/consensus). We define a stochastic dynamical process as follows:
- Every k-tuple of clusters coalesces at rate $\alpha(k)n^{1-k}$, independently of everything else that happens in the system. The coalescing cells are merged to form a single cluster with size equal to the sum of the sizes of the merged clusters.
- Clusters fragment (terrorist cells are dispersed/consensus breaks) at constant rate $\lambda > 0$, independently of everything else that happens in the system. Fragmentation of a cluster of size ℓ results in ℓ 'singleton' clusters of size one.

Terrorists, consensus and biological clustering



Terrorists, consensus and biological clustering

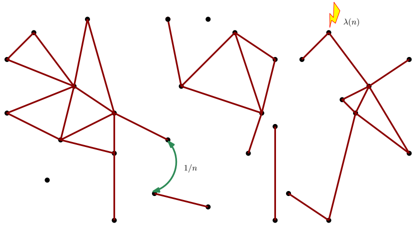
- Without fragmentation, the model falls within the domain of study of Smoluchowski coagulation equations, originally devised to consider chemical processes occurring in polymerisation, coalescence of aerosols, emulsication, flocculation.
- In all cases: one is interested in the macroscopic behaviour of the model (large n), in particular in exploring universality properties.

Terrorists, consensus and biological clustering

- Without fragmentation, the model falls within the domain of study of Smoluchowski coagulation equations, originally devised to consider chemical processes occurring in polymerisation, coalescence of aerosols, emulsication, flocculation.
- In all cases: one is interested in the macroscopic behaviour of the model (large n), in particular in exploring universality properties.

Model history (but only for dyadic coalescence)

- This model is a variant of the one presented in: Bohorquez, Gourley, Dixon, Spagat & Johnson (2009) Common ecology quantifies human insurgency *Nature* **462**, 911-914.
- It is also related to: Ráth and Tóth (2009) Erdős-Rènyi random graphs + forest fires = self-organized criticality, **14** Paper no. 45, 1290-1327.



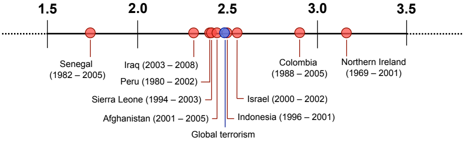
In a system of size n 'vacant' edges become 'occupied' at rate $1/n$, each site 'hit by lightning' at rate $\lambda(n)$ annihilating to singletons the cluster in which it is contained.

Heavy-tailed terrorism

- In the insurgency model, two blocks merge if a terrorist in each block make a connection, which they do at a fixed rate. This means that coalescence is more likely for a big terrorist cell.
- The macroscopic-scale, large time limit of the insurgency model for a "slow rate of fragmentation" shows that the distribution of block size is heavy tailed:

$$\text{“}\mathbb{P}(\text{typical block} = x) \approx \text{const.} \times x^{-\alpha}, \qquad x \to \infty.\text{”}$$

- Taken from Bohorquez, Gourley, Dixon, Spagat & Johnson (2009):



A challenge

- The Ráth-Tóth model take account of cluster size but not proximity (inherent Erdös-Renyi percolation type structure)
- Our model borrows from the spirit of the exchangeable Λ-coalescent (without actually having that mechanism) and allows for multiple coagulation irrespective of cluster sizes.
- Are there variants of this story which can incorporate multiple cluster mergers with cluster size dependence and and/or proximity?

A challenge

- The Ráth-Tóth model take account of cluster size but not proximity (inherent Erdös-Renyi percolation type structure)
- Our model borrows from the spirit of the exchangeable Λ-coalescent (without actually having that mechanism) and allows for multiple coagulation irrespective of cluster sizes.
- Are there variants of this story which can incorporate multiple cluster mergers with cluster size dependence and and/or proximity?

A challenge

- The Ráth-Tóth model take account of cluster size but not proximity (inherent Erdös-Renyi percolation type structure)
- Our model borrows from the spirit of the exchangeable Λ-coalescent (without actually having that mechanism) and allows for multiple coagulation irrespective of cluster sizes.
- Are there variants of this story which can incorporate multiple cluster mergers with cluster size dependence and and/or proximity?

Back to our model: Generating function

- For each $n \in \mathbb{N}$, and $k \in \{1, \ldots, n\}$, the state of the system is specified by the number of clusters of size k at time t.
- Introduce the random variables

$$w_{n,k}(t) := \frac{1}{n}\#\{\text{clusters of size } k \text{ at time } t\}, \quad 1 \leq k \leq n.$$

- Rather than working with these quantities directly, use the empirical generating function

$$G_n(x,t) = \sum_{k=1}^{n} x^k w_{n,k}(t), \qquad n \geq 1, x \in (0,1), t \geq 0$$

Back to our model: Generating function

- For each $n \in \mathbb{N}$, and $k \in \{1, \ldots, n\}$, the state of the system is specified by the number of clusters of size k at time t.
- Introduce the random variables

$$w_{n,k}(t) := \frac{1}{n}\#\{\text{clusters of size } k \text{ at time } t\}, \quad 1 \leq k \leq n.$$

- Rather than working with these quantities directly, use the empirical generating function

$$G_n(x, t) = \sum_{k=1}^{n} x^k w_{n,k}(t), \qquad n \geq 1, x \in (0, 1), t \geq 0$$

Back to our model: Generating function

- For each $n \in \mathbb{N}$, and $k \in \{1, \dots, n\}$, the state of the system is specified by the number of clusters of size k at time t.
- Introduce the random variables

$$w_{n,k}(t) := \frac{1}{n}\#\{\text{clusters of size } k \text{ at time } t\}, \quad 1 \le k \le n.$$

- Rather than working with these quantities directly, use the empirical generating function

$$G_n(x,t) = \sum_{k=1}^{n} x^k w_{n,k}(t), \qquad n \ge 1, x \in (0,1), t \ge 0$$

Theorem 1

Theorem

Suppose that the coalescence rates $\alpha : \mathbb{N} \to \mathbb{R}^+$ satisfy

$$\alpha(k) \leq \exp(\gamma k \ln \ln(k)) \, , \qquad \forall k \, ,$$

where $\gamma < 1$ is an arbitrary constant. Let $G : [0,1] \times \mathbb{R}^+ \to \mathbb{R}$ be the solution of the deterministic initial value problem

$$G(x,0) = x \, ,$$

$$\frac{\partial G}{\partial t}(x,t) = \lambda(x - G(x,t)) + \sum_{k=2}^{\infty} \frac{\alpha(k)}{k!} \left(G(x,t)^k - kG(1,t)^{k-1} G(x,t) \right) .$$

Then $G_n(x,t)$ converges to $G(x,t)$ in L^2, uniformly in x and t, as $n \to \infty$, that is

$$\sup_{x \in [0,1], t \geq 0} \mathbb{E}\left[(G(x,t) - G_n(x,t))^2 \right] \to 0, \quad as \quad n \to \infty.$$

Main technique in proof

- For $f(x, \boldsymbol{w_n}) := \sum_{k=1}^{n} x^k w_{n,k}$, we have

$$\mathcal{A}_n f(x, \boldsymbol{w_n}) = \lambda(x - f(x, \boldsymbol{w_n})) + \sum_{k=2}^{n} \frac{\alpha(k)}{k!}(f(x, \boldsymbol{w_n})^k - kf(1, \boldsymbol{w_n})^{k-1} f(x, \boldsymbol{w_n}))$$

$$+ \beta_n(x, \boldsymbol{w_n}),$$

  where

$$\sup_{\boldsymbol{w_n}} |\beta_n(x, \boldsymbol{w_n})| \leq \frac{A}{n},$$

  where A is a constant independent of n and x.

- Look at the mean-field equations to "guess" the limiting behaviour of $G_n(x, t)$ (equivalently consider the leading order terms of the generator).
- Apply Dynkin's formula,play with leading terms in generator and invoke Gronwall's Lemma:

$$\mathbb{E}[(G(x,t) - G_n(x,t))^2] = \mathbb{E}\left[\int_0^t \left(\frac{\partial}{\partial s} + \mathcal{A}_n\right)[(G(x,s) - G_n(x,s))^2] ds\right],$$

Main technique in proof

- For $f(x, \boldsymbol{w_n}) := \sum_{k=1}^{n} x^k w_{n,k}$, we have

$$\mathcal{A}_n f(x, \boldsymbol{w_n}) = \lambda(x - f(x, \boldsymbol{w_n})) + \sum_{k=2}^{n} \frac{\alpha(k)}{k!}(f(x, \boldsymbol{w_n})^k - kf(1, \boldsymbol{w_n})^{k-1} f(x, \boldsymbol{w_n})) + \beta_n(x, \boldsymbol{w_n}),$$

  where

$$\sup_{\boldsymbol{w_n}} |\beta_n(x, \boldsymbol{w_n})| \le \frac{A}{n},$$

  where A is a constant independent of n and x.
- Look at the mean-field equations to "guess" the limiting behaviour of $G_n(x, t)$ (equivalently consider the leading order terms of the generator).
- Apply Dynkin's formula,play with leading terms in generator and invoke Gronwall's Lemma:

$$\mathbb{E}[(G(x,t) - G_n(x,t))^2] = \mathbb{E}\left[\int_0^t \left(\frac{\partial}{\partial s} + \mathcal{A}_n\right)[(G(x,s) - G_n(x,s))^2]ds\right],$$

Main technique in proof

- For $f(x, \boldsymbol{w_n}) := \sum_{k=1}^{n} x^k w_{n,k}$, we have

$$\mathcal{A}_n f(x, \boldsymbol{w_n}) = \lambda(x - f(x, \boldsymbol{w_n})) + \sum_{k=2}^{n} \frac{\alpha(k)}{k!}(f(x, \boldsymbol{w_n})^k - kf(1, \boldsymbol{w_n})^{k-1} f(x, \boldsymbol{w_n}))$$
$$+ \beta_n(x, \boldsymbol{w_n}),$$

  where

$$\sup_{\boldsymbol{w_n}} |\beta_n(x, \boldsymbol{w_n})| \leq \frac{A}{n},$$

  where A is a constant independent of n and x.
- Look at the mean-field equations to "guess" the limiting behaviour of $G_n(x, t)$ (equivalently consider the leading order terms of the generator).
- Apply Dynkin's formula,play with leading terms in generator and invoke Gronwall's Lemma:

$$\mathbb{E}[(G(x,t) - G_n(x,t))^2] = \mathbb{E}\left[\int_0^t \left(\frac{\partial}{\partial s} + \mathcal{A}_n\right)[(G(x,s) - G_n(x,s))^2] \mathrm{d}s\right],$$

- The next theorem deals with the stationary cluster size distribution.
- Let

$$p_{n,k}(t) := \frac{\#\{\text{clusters of size } k \text{ at time } t\}}{\#\{\text{clusters at time } t\}}, \quad 1 \leq k \leq n.$$

- Define

$$p_k := \lim_{t\to\infty} \lim_{n\to\infty} p_{n,k}(t)\,,$$

as a distributional limit, which exists thanks to the previous theorem and that

$$\sum_{k=1}^{n} x^k p_{n,k}(t) = \frac{G_n(x,t)}{G_n(1,t)}, \qquad n \geq 1, x \in (0,1), t \geq 0\,.$$

- The next theorem deals with the stationary cluster size distribution.
- Let

$$p_{n,k}(t) := \frac{\#\{\text{clusters of size } k \text{ at time } t\}}{\#\{\text{clusters at time } t\}}, \quad 1 \le k \le n.$$

- Define

$$p_k := \lim_{t\to\infty} \lim_{n\to\infty} p_{n,k}(t)\,,$$

as a distributional limit, which exists thanks to the previous theorem and that

$$\sum_{k=1}^{n} x^k p_{n,k}(t) = \frac{G_n(x,t)}{G_n(1,t)}, \qquad n \ge 1, x \in (0,1), t \ge 0\,.$$

- The next theorem deals with the stationary cluster size distribution.
- Let

$$p_{n,k}(t) := \frac{\#\{\text{clusters of size } k \text{ at time } t\}}{\#\{\text{clusters at time } t\}}, \quad 1 \leq k \leq n.$$

- Define

$$p_k := \lim_{t\to\infty} \lim_{n\to\infty} p_{n,k}(t)\,,$$

as a distributional limit, which exists thanks to the previous theorem and that

$$\sum_{k=1}^{n} x^k p_{n,k}(t) = \frac{G_n(x,t)}{G_n(1,t)}, \qquad n \geq 1, x \in (0,1), t \geq 0\,.$$

Theorem 2

Theorem

If α satisfies

$$\alpha(k) \leq \exp(\gamma k \ln \ln(k)), \qquad \forall k,$$

and m is the smallest integer such that $\alpha(m) > 0$, then the stationary cluster size distribution obeys

$$\lim_{\lambda \searrow 0} p_k = \begin{cases} \frac{1}{k} \left(\frac{m-1}{m}\right)^k \left(\frac{1}{m}\right)^{\frac{k-1}{m-1}} \binom{m\left(\frac{k-1}{m-1}\right)}{\frac{k-1}{m-1}} & \text{if } m-1 \text{ divides } k-1 \\ 0 & \text{otherwise} \end{cases}$$

and in particular, as $k \to \infty$

$$\lim_{\lambda \searrow 0} p_k \approx \begin{cases} k^{-3/2} & \text{if } m-1 \text{ divides } k-1 \\ 0 & \text{otherwise.} \end{cases}$$

Terrorists never congregate in even numbers

- Suppose we allow coalescence in groups of three or more but not pairs ($m = 3$).
- In the large n and small λ limit we will see no clusters of even size whatsoever in the stationary distribution.
- The model has the apparently paradoxical feature that clusters of even size are vanishingly rare, despite the fact that $\lim_{\lambda \searrow 0} p_1 \approx 2/3$.
- This is a consequence of the weight of the tail of the cluster size distribution.
- The universal exponent 3/2 suggests a typical cluster size $\sum_1^n kp_k \approx O(n^{1/2}) \Rightarrow \sharp$ clusters $\approx O(n^{1/2})$.
  Coalescence of triples: $\binom{n^{1/2}}{3} \times \alpha(3)n^{1-3} \approx O(n^{-1/2})$
  Coalescence of quadruples: $\binom{n^{1/2}}{4} \times \alpha(4)n^{1-4} \approx O(n^{-1})$
  With 2/3 of blocks being singletons, this creates an imbalance with manifests in the disappearance of even sized blocks.

Terrorists never congregate in even numbers

- Suppose we allow coalescence in groups of three or more but not pairs ($m = 3$).
- In the large n and small λ limit we will see no clusters of even size whatsoever in the stationary distribution.
- The model has the apparently paradoxical feature that clusters of even size are vanishingly rare, despite the fact that $\lim_{\lambda \searrow 0} p_1 \approx 2/3$.
- This is a consequence of the weight of the tail of the cluster size distribution.
- The universal exponent $3/2$ suggests a typical cluster size $\sum_1^n kp_k \approx O(n^{1/2}) \Rightarrow \sharp$ clusters $\approx O(n^{1/2})$.

  Coalescence of triples: $\binom{n^{1/2}}{3} \times \alpha(3)n^{1-3} \approx O(n^{-1/2})$

  Coalescence of quadruples: $\binom{n^{1/2}}{4} \times \alpha(4)n^{1-4} \approx O(n^{-1})$

  With $2/3$ of blocks being singletons, this creates an imbalance with manifests in the disappearance of even sized blocks.

Terrorists never congregate in even numbers

- Suppose we allow coalescence in groups of three or more but not pairs ($m = 3$).
- In the large n and small λ limit we will see no clusters of even size whatsoever in the stationary distribution.
- The model has the apparently paradoxical feature that clusters of even size are vanishingly rare, despite the fact that $\lim_{\lambda \searrow 0} p_1 \approx 2/3$.
- This is a consequence of the weight of the tail of the cluster size distribution.
- The universal exponent 3/2 suggests a typical cluster size $\sum_1^n kp_k \approx O(n^{1/2}) \Rightarrow \sharp$ clusters $\approx O(n^{1/2})$.
  Coalescence of triples: $\binom{n^{1/2}}{3} \times \alpha(3)n^{1-3} \approx O(n^{-1/2})$
  Coalescence of quadruples: $\binom{n^{1/2}}{4} \times \alpha(4)n^{1-4} \approx O(n^{-1})$
  With 2/3 of blocks being singletons, this creates an imbalance with manifests in the disappearance of even sized blocks.

Terrorists never congregate in even numbers

- Suppose we allow coalescence in groups of three or more but not pairs ($m = 3$).
- In the large n and small λ limit we will see no clusters of even size whatsoever in the stationary distribution.
- The model has the apparently paradoxical feature that clusters of even size are vanishingly rare, despite the fact that $\lim_{\lambda \searrow 0} p_1 \approx 2/3$.
- This is a consequence of the weight of the tail of the cluster size distribution.
- The universal exponent $3/2$ suggests a typical cluster size $\sum_1^n kp_k \approx O(n^{1/2}) \Rightarrow \sharp$ clusters $\approx O(n^{1/2})$.
  Coalescence of triples: $\binom{n^{1/2}}{3} \times \alpha(3) n^{1-3} \approx O(n^{-1/2})$
  Coalescence of quadruples: $\binom{n^{1/2}}{4} \times \alpha(4) n^{1-4} \approx O(n^{-1})$
  With $2/3$ of blocks being singletons, this creates an imbalance with manifests in the disappearance of even sized blocks.

Terrorists never congregate in even numbers

- Suppose we allow coalescence in groups of three or more but not pairs ($m = 3$).
- In the large n and small λ limit we will see no clusters of even size whatsoever in the stationary distribution.
- The model has the apparently paradoxical feature that clusters of even size are vanishingly rare, despite the fact that $\lim_{\lambda \searrow 0} p_1 \approx 2/3$.
- This is a consequence of the weight of the tail of the cluster size distribution.
- The universal exponent $3/2$ suggests a typical cluster size $\sum_1^n kp_k \approx O(n^{1/2}) \Rightarrow \sharp$ clusters $\approx O(n^{1/2})$.
  Coalescence of triples: $\binom{n^{1/2}}{3} \times \alpha(3) n^{1-3} \approx O(n^{-1/2})$
  Coalescence of quadruples: $\binom{n^{1/2}}{4} \times \alpha(4) n^{1-4} \approx O(n^{-1})$
  With $2/3$ of blocks being singletons, this creates an imbalance with manifests in the disappearance of even sized blocks.

Thank you!