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Many-body descriptions of rare events in complex dynamical systems

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14. ABSTRACT
This project provides a new approach to understanding rare and extreme events in real-world complex systems, by generalizing key ideas of many-body theory to account for the fact that the underlying objects may be heterogeneous and interconnected, and hence act in correlated ways to produce the emergence of extreme behavior. The project produced approximately 30 publications in top journals, including Nature and Science as well as Physical Review Letters, despite only featuring funding for 1 PI and research assistant help. It also attracted a large amount of attention from the mainstream and scientific media both within the US and overseas (e.g. New York Times, BBC, CNN, PBS) and also from U.S. agencies at the Federal and State level. The initial PI was invited to give briefings about the research to the U.S. State Department and other agencies such as the FBI, and the research results were apparently mentioned and discussed in a recent Congressional hearing. The project achieved its overall goal of conducting research that advances understanding of extreme dynamical behaviors, by developing and generalizing ideas from many-body gelation. Particular focus was paid to the implications for the emergence of extreme behaviors (akin to gelation) from the interplay between an internal characteristic (e.g. intrinsic heterogeneity such as a simple form of strategy allocation or characteristic), since this was the topic that emerged as the richest computationally and mathematically, and arguably is the most pressing scientific and societal challenge. Also, as promised in the proposal, the possibility that different types of collective behavior emerge or specifically, different types of gel emerge -- was addressed in a preliminary way, and the project has now established a clear research framework for further work in this area within the computational mathematics research comm

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PI: Joshua Cohn (previously Neil Johnson), University of Miami

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Contents:

1. Overview

Rare and extreme events emerge from complex dynamical systems comprising inter-connected objects. Many-body theory has proven a powerful tool in describing the equilibrium behavior of physical systems comprising interacting objects -- however the complication in complex systems from the social, economic, cyber, mechanical and life sciences is that the interacting objects are not identical; they have adaptive capability; and they are not in equilibrium. This project provides a step forward toward understanding rare and extreme events in such real-world complex systems, by generalizing key ideas of many-body theory (e.g. gelation) to account for the fact that the underlying objects may be interconnected and hence act in correlated ways.

2. Achievements and products

The project achieved its overall goal of conducting research that advances understanding of extreme dynamical behaviors -- rare events -- by developing and generalizing ideas from many-body theory. Particular focus was paid to the implications for the emergence of extreme behaviors (akin to gelation) from the interplay between an internal characteristic (e.g. intrinsic heterogeneity such as a simple form of strategy allocation or characteristic), since this was the topic that emerged as the richest computationally and mathematically, and arguably is the most pressing scientific and societal challenge. Also, as promised in the proposal, the possibility that different types of collective behavior emerge – or specifically 'gels' emerge -- was addressed in a preliminary way, and the project has now established a clear research framework for further work. This topic is the main focus of the present final report since it ended up occupying most of the time.

Specifically, as evidenced by the publications from this project, the project met its objectives:

Objective 1 which was to analyze mathematically and computationally a generic multi-agent system of interacting objects (agents) in which the agents are heterogeneous (e.g. intrinsic heterogeneity such as a simple form of strategy allocation or characteristic). Traditional many-body physical systems with identical particles, are a special case of this;

Objective 2 which was to investigate the interplay between observed global dynamics of the system, and this heterogeneity. As showed for example in the Physical Review Letters article published in 2018, and the Nature paper in 2019, this understanding was key to unlocking the behavior of the effective gelation and hence the surprise emergence of macro-level collective behavior which is an extreme event in time;

Objective 3 which was to conduct a forensic analysis of the anatomy of rare events in the model, relating them back to the history of the system up to that point, the strategy allocation across the population, and recent strategy usage;

Objective 4 which was to determine the extent to which heterogeneities dictate the likelihood of the emergence of a gel – and hence an extreme or rare event – and its onset;

Objective 5 which was to investigate a generalized version of many-body theory – gelation theory, as it turned out -- that remains mathematically and/or computationally tractable for the emergence of an extreme where the strongest inter-agent correlations are incorporated into composite particle (gel) which then have weaker interactions than the underlying agents;

Objective 6 which was to investigate in a very preliminary way, reverse engineering black-box data to discern an underlying many-body game. This was done on real data containing extreme behaviors;

Objective 7 which was to determine if there are different types of extreme behaviors that can emerge. We found that the gels' emergence time and growth depends on the way in which the heterogeneities combine, for example homophily vs heterophily. This is documented in detail in the Physical Review Letters (2018) article and others (see Sec. 3);

Objective 8 which was to explore other forms of emergent gels. This was down by looking at everything from public protein databases, through to extremism online. An example of the latter is the 2019 Nature paper. An example of this for algorithms, is the 2017 Science paper;

Objective 9 was to explore how the emergence of the extreme macroscopic behavior (gel) may be avoided or at least delayed, using minimal intervention and without manipulating individual objects. This is discussed in the 2018 Physical Review Letters article and the 2019 Nature paper.

In this way, the project advanced understanding of extreme dynamical behaviors -- rare events -- by developing and generalizing ideas from many-body theory. As a result, the project illuminates the driving factors underlying rare events in real-world complex systems including networks, by extending a many-body approach in order to incorporate additional elements of real-world complexity. The focus was on endogenous rare events that cannot be attributed to any external cause, but instead arise because of internal dynamical correlations that somehow build up within the system by itself – and often do so too quickly for anyone to simply 'turn off' the system, or to intervene effectively. A desire of the project was to investigate rare/extreme event behaviors in real-world that are of direct relevance to DoD, and the U.S. government and its agencies. The project achieved this with the analysis of extremism. As such, the research project successfully combined aspects of mathematics, computation, physics, and 'big' data from real-world systems.

In addition to the publications and media reports of the research discussed in Secs. 2 and 3, Johnson's scientific research on this topic was recognized by the American Physical Society. Specifically, Johnson was awarded the prestigious Burton Award (March 2018) and was also made a Fellow of the American Physical Society (March 2018).

The project's research led to approximately 30 publications. A listing is given in Sec. 3, but below we discuss a few:

Physical Review Letters (2018):
"Generalized gelation theory describes onset of online extremist support", Phys. Rev. Lett. (2018) July 27 online; P.D. Manrique, M. Zheng, Z. Cao, E.M. Restrepo, N.F. Johnson
This paper was featured in a number of national and international media outlets, as well as in the highlight section of the American Physical Society's main webpage. This publication looks at rare events in the form of the collective emergence of a crowd of correlated agents. It involves a mix of novel computational and mathematical analysis. In particular, the theory that is developed could in principle provide generic insight into how rare events develop in general systems of interest to AFOSR and DoD that contain many interconnected parts. It shows that the corresponding rare event is a collective phenomenon that develops akin to a 'gel' suddenly emerging from a system (in everyday terms, such as milk curdling). Johnson generalized the existing mathematical theory of gel formation in physical and chemical systems, by accounting for the general case of heterogeneous objects. Since heterogeneity of interacting objects is the norm in real-world systems rather than a special case, the project could be of interest to DoD and other government stakeholders.

Interestingly, the theory in this paper also involved developing a generalized version of the inviscid Burgers equation which is of potential interest to many other projects within AFOSR and DoD in the areas of fluid mechanics, nonlinear acoustics, gas dynamics, and even traffic flow. The theory incorporates the heterogeneity of objects using a variable x assigned to each individual object, yet this assumption can be generalized to account for a vector of attributes. We obtained the temporal evolution of the gel cluster size G(t) by means of the exponential generating function whose partial time derivative takes the form of the inviscid Burgers equation which can be solved by the method of characteristics. The solution can be expressed in terms of the W-Lambert function. It is also interesting that although the theory that we developed is general, it speaks to the pressing practical problem of extremism in the cyberspace – which is a key area of interest to the Air Force. The research shows that existing strategies aimed at defeating rare events associated with online activity under the assumption that they are driven by a few 'bad apple' individuals, are misguided. Instead, our new physics-inspired theory describes how otherwise typical humans manage to 'gel' so suddenly online in support of extremism and hate. Not only is the theory new for the physical, mathematical, chemical, biological and social sciences, its implications for local, national and international security policy are also completely new. Figure 1 (below left) shows a snapshot of the network of correlations, where individual agents (white circles) 'gel' together (black dots are pockets of correlation) and the interactions are shown as red links. In Figure 1 (below right), red disks show how a particular pocket of correlations suddenly emerges from the system in time. Dashed horizontal line shows our calculated theoretical value for the correlated cluster's moment of 'birth'.

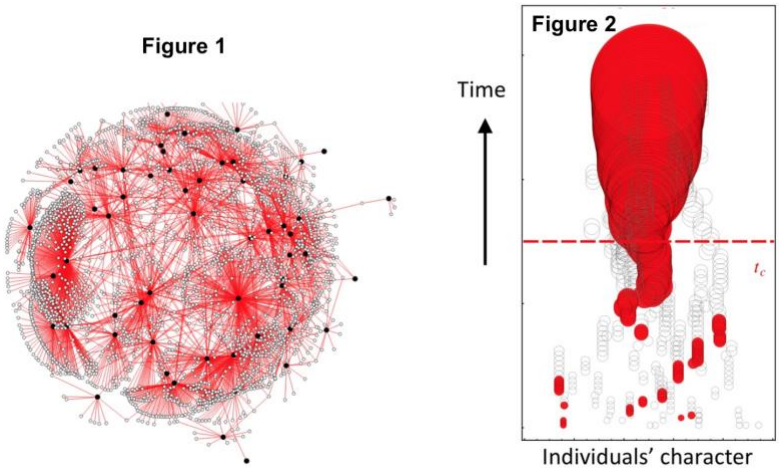

Figure 1: Snapshot of the network of correlations.

Figure 2 below shows a snapshot of the actual empirical 'gel' formation underlying online extremist support for ISIS, globally, that we measured and modeled as an application of our theory. Red here denotes the correlated pockets that will in the future become so extreme that they get banned.

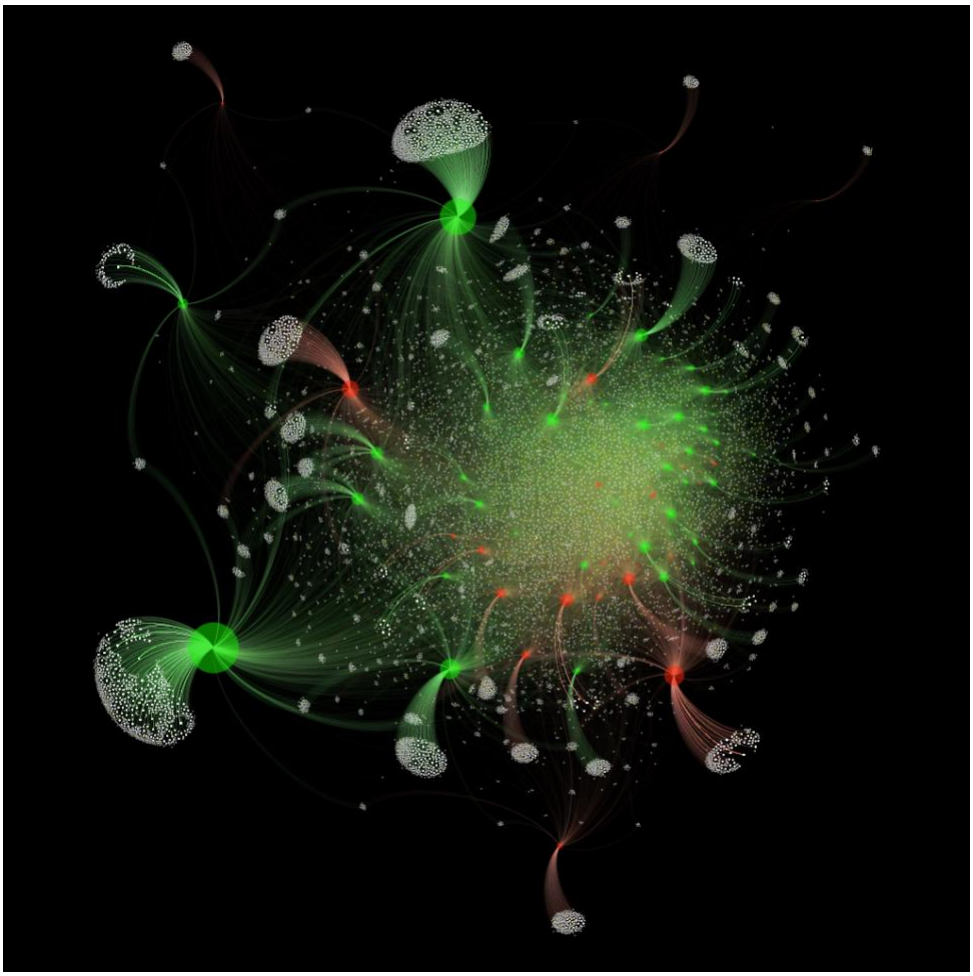

Figure 2: Snapshot of the actual empirical 'gel' formation underlying online extremes

Still on the core topic of rare events, with the common theme of their collective generation and hence unraveling the cause of rare events, a further publication is in the area of quantum information and computing which is also of interest to AFOSR and DoD. It appeared in the journal Frontiers in Physics:
"Pulsed Generation of Quantum Coherences and Non-classicality in Light-Matter Systems", Frontiers (in press, 2018) doi: 10.3389/fphy.2018.00092; Fernando Javier Gómez-Ruiz, Oscar Leonardo Acevedo, Oscar Leonardo Acevedo, Ferney Rodríguez, Ferney Rodríguez, Luis Quiroga, Luis Quiroga, Neil Johnson, Neil Johnson

Another publication considered the impact of the emergence of a rare event in a system, in terms of how it sends the system "off track". The paper develops a new theory and shows that it compares favorably to empirical data from decentralized biological systems. The paper appears in the journal Complexity:
"Decentralized competition produces nonlinear dynamics akin to klinotaxis", Complexity 2018, Article ID 9803239 (2018) https://doi.org/10.1155/2018/9803239; Pedro Manrique, Mason Klein, Yao Sheng Li, Chen Xu, Pak Ming Hui and Neil F. Johnson

Then a more detailed paper with a full theory was published in *Science Advances* in 2019. This was:
"Getting closer to the goal by being less capable" Science Advances 2, eaau5902

(2019) DOI: 10.1126/sciadv.aau5902; *Pedro D. Manrique, Mason Klein, Yao Sheng Li, Chen Xu, Pak Ming Hui, Neil F. Johnson*

A further publication considered the dynamics of the trajectory followed by an object on its path through some state space of a complex system. It appears in the journal Physical Review E:
"Universality and correlations in individuals wandering through an online extremist space". Phys. Rev. E 97, 032315 (2018); Z.Cao, M.Zheng, Y.Vorobyeva, C.Song, N.F.Johnson

The next publication reveals how rare events and pockets of extreme correlations, can undergo explosive percolation. It appears in the journal Physical Review E:
"Individual heterogeneity generates explosive system network dynamics", Phys. Rev. E 97, 032311 (2018); Pedro D. Manrique, Neil F. Johnson

A related publication considers the dynamics of the trajectory followed by an object on its path through some state space of a complex system. It appears in the journal Complexity:
"Complexity in individual trajectories toward online extremism", Complexity 2018, Article number 3929583 (2018); Z.Cao, M.Zheng, Y.Vorobyeva, C.Song, N.F.Johnson

The following publication considers the collective dynamics of correlated groups throughout the lifetime of a complex system. It appears in the journal Scientific Reports:
"Multiscale dynamical network mechanisms underlying aging from birth to death", Scientific Reports 8, 3552 (2018); M. Zheng, Z. Cao, Y. Vorobyeva, P. Manrique, C. Song, N.F. Johnson

This next publication is also on the topic of rare events in quantum systems, specifically quantum information and computing which are of interest to AFOSR and DoD. It appears in the journal J. Phys. B:
"Dynamics of entanglement and the Schmidt gap in a driven light-matter system". J. Phys. B: At. Mol. Opt. Phys. 51, 024001 (2018); Fernando Javier Gómez-Ruiz, Juan Jose Mendoza-Arenas, Oscar Acevedo, Ferney J Rodriguez, Luis Quiroga and Neil F Johnson

The spending and schedule for the project were both reasonably kept on track.

3. List of Publications, Media Attention and Federal/State agency interest

Elements of the research attracted great interest at the State, Federal and at the international level. For example, the paper in Physical Review Letters (online July 27, 2018) was featured in a number of national and international media outlets as well as in the highlight section of the American Physical Society's main webpage. As recognition of the scientific innovation performed by the PI during the period of this project, the American Physical Society awarded the PI the Burton Award during Year 2 (March 2018) and also made the PI a Fellow of the American Physical Society. The PI's work was also featured in other national and international media (e.g. Quanta magazine) in Year 2. Examples of direct interest from U.S. entities include:

1. Army Research Laboratory, Adelphi MD. 4/24/2019
2. SOUTHCOM Headquarters. Doral FL 8/26/2016. Invited talk on "Transnational organized crime".
3. U.S. State Department presentation 9/20/2019
4. U.S. Senate 2019 Hearing on Extremism

Media reports of the research include:
1. [Print Media] Physics helps to model online terrorist activity, Physics World, 2019 Mar, Print and Online https://physicsworld.com/a/physics-helps-to-model-online-terrorist-activity/
2. [Print Media] Artificial "Dumbness" May Be a Solution for Engineering Smart Machines, Scientific American, 2019 Feb, Print and Online https://www.scientificamerican.com/article/artificial-dumbness-may-be-a-solution-for-engineering-smart-machines/? utm_source=newsletter&utm_medium=email&utm_campaign=daily-digest&utm_content=link&utm_term=2019-02-13_featured- this-week&spMailingID=58467145&spUserID=MzI2OTIwMDY2NTI3S0&spJobID=1581626755&spReportId=MTU4MTYyNjc1NQS2
3. [Internet] How quantum terrorists could bring down the future internet, Technology Review, 2019 Feb, https://www.technologyreview.com/s/612887/how-quantum-terrorists-could-bring-down-the-future-internet/
4. [Digital Media] Terrorism Could Soon Go Digital and Destroy Whole Economies, Homeland Security Today, 2019 Feb, https://www.hstoday.us/subject-matter-areas/counterterrorism/terrorism-could-soon-go-digital-and-destroy-whole-economies/
5. [Digital Media] Terrorism Could Soon Go Digital and Destroy Whole Economies, Yahoo Finance (India), 2019 Feb, https://in.finance.yahoo.com/news/terrorism-soon-go-digital-destroy-whole-economies-101337364.html
6. [Print Media] Smarter Parts Make Collective Systems Too Stubborn, Quanta Magazine, 2019 Feb, Print and Online https://www.quantamagazine.org/smarter-parts-make-collective-systems-too-stubborn-20190226/
7. [Digital Media] Is the Quantum Internet Terrorist-Proof?, Edgy, 2019 Feb, https://edgy.app/quantum-internet-terrorist-proof
8. [Digital Media] Quantum Terrorism A New Threat, Inside Quantum Technology, 2019 Feb
9. [Digital Media] Simpler parts make for a more efficient system, Science Daily, 2019 Feb
10. [Digital Media] Decentralized systems are more efficient at reaching a target, Phys.Org, 2019 Feb
11. [Digital Media] Getting Closer to the Goal by Being Less Capable, Eureka Alert, 2019 Feb
12. [Print Media] New study pinpoints patterns among violent events in war and terrorism, revealing the 'untamed nature of modern conflict', Daily Mail, 2018 Oct, Print and Online https://www.dailymail.co.uk/sciencetech/article-6291709/New-study-pinpoints-patterns-violent-events-war-terrorism.html
13. [Print Media] Franken-algorithms: the deadly consequences of unpredictable code, The Guardian, 2018 Aug, Print and Online https://www.theguardian.com/technology/2018/aug/29/coding-algorithms-frankenalgos-program-danger
14. [Digital Media] Fighting ISIS and Fake Facebook Accounts with Physics, Inside Science, 2018 Aug, https://www.insidescience.org/news/fighting-isis-and-fake-facebook-accounts-physics
15. [Digital Media] Identifying Early Signs of Online Extremist Groups, American Physical Society: Focus, 2018 Jul https://physics.aps.org/articles/v11/76

Since August 2019 alone, the following additional media reports have appeared about this research:
Sydney Morning Herald: Former extremist teams up with Facebook to help users avoid the recruitment 'rabbit hole'
https://www.smh.com.au/technology/former-extremist-teams-up-with-facebook-to-help-users-avoid-the-recruitment-rabbit-hole-20190917-p52s8m.html
Forbes: Former extremist teams up with Facebook
https://www.forbes.com/sites/heatherleighton/2019/08/28/online-hate-report-sheds-light-on-prevalence-of-social-media-hate/#6b1eed1f77c0
First Kind Mapping Model Tracks How Hate Spreads and Adapts Online
https://mediarelations.gwu.edu/first-its-kind-mapping-model-tracks-how-hate-spreads-and-adapts-online
Novel Mapping Model Tracks How Hate Spreads and Adapts Online

https://gwtoday.gwu.edu/novel-mapping-model-tracks-how-hate-spreads-and-adapts-online

as well as:

Financial Times
Slaying the online hate hydra requires cunning and agility
https://www.ft.com/content/d3d1c93a-c7f3-11e9-af46-b09e8bfe60c0

U.S. News & World Report
How Online Hate Speech Spreads Around the Globe
https://www.usnews.com/news/best-countries/articles/2019-08-28/researchers-suggest-new-ways-countries-can-fight-against-online-hate-speech
- This article also appeared on WTOP-FM's website (Washington, D.C.).

Fox News Channel Online
Highways of hate': Current policing of hate groups is ineffective, expert warns
https://www.foxnews.com/tech/policing-of-online-hate-groups-ineffective-expert-warns

GW Hatchet
Research team sets recommendations for removing online hate groups
https://www.gwhatchet.com/2019/08/25/research-team-sets-recommendations-for-removing-online-hate-groups/

The Guardian
The physics professor who says online extremists act like curdled milk
https://www.theguardian.com/science/2019/aug/22/online-hate-extremism-physics-science

Der Standard (Austria)
Wie sich rechter Hass im Netz ausbreitet
https://www.derstandard.de/story/2000107693394/wie-sich-rechter-hass-im-netz-ausbreitet

European Scientist
How do hate groups persist on social media platforms? Researchers shed some light.
https://www.europeanscientist.com/en/research/how-do-hate-groups-persist-on-social-media-platforms/

Earth.com
Online hate thrives globally through interconnected clusters, study shows
https://www.earth.com/news/online-hate-global/

Geek.com
Try These Four Policies to Dismantle Online Hate Groups
https://www.geek.com/tech/try-these-four-policies-to-dismantle-online-hate-groups-1801293/

Science Magazine
'Dark pools' of hate flourish online. Here are four controversial ways to fight them
https://www.sciencemag.org/news/2019/08/dark-pools-hate-flourish-online-here-are-4-controversial-ways-fight-them

MIT Technology Review
Here's how social-media firms should tackle online hate, according to physics

https://www.technologyreview.com/s/614208/heres-how-social-media-firms-should-tackle-online-hate-according-to-physics/

Metro (U.K.)
Global online 'hate highways' are squeezing the web and scientists are trying to stop them
https://metro.co.uk/2019/08/22/global-online-hate-highways-are-squeezing-the-web-and-scientists-are-trying-to-stop-them-10613861/

Electronics Weekly
Mapping on-line hate reveals team work is the only useful countermeasure
https://www.electronicsweekly.com/news/business/market-research/mapping-line-hate-reveals-team-work-useful-countermeasure-2019-08/

The Verge
Researchers propose a new approach for dismantling online hate networks
https://www.theverge.com/interface/2019/8/22/20827509/online-hate-networks-neil-johnson-george-washington-miami-facebook-vkontakte

Nature
Daily Briefing, August 22
https://www.nature.com/articles/d41586-019-02544-1

Nature
Strategies for combating online hate
https://www.nature.com/articles/d41586-019-02447-1

Nature Podcast
Podcast: Tackling online hate speech, and identifying early fossils
https://www.nature.com/articles/d41586-019-02513-8

NBC News
'Hate is in the ether': Research finds hate is resilient on the internet
https://www.nbcnews.com/tech/tech-news/hate-ether-research-finds-hate-resilient-internet-n1044871

CNBC
A new theory describes how hate travels across social media platforms and around the world — and one researcher compares it to water boiling
https://www.cnbc.com/2019/08/21/new-study-in-nature-maps-how-hate-travels-across-social-media.html

Scientific American
Researchers Model Online Hate Networks In Effort to Battle Them
https://www.scientificamerican.com/article/researchers-model-online-hate-networks-in-effort-to-battle-them/

Inverse
Global Hate Highways" Reveal How Online Hate Clusters Multiply and Thrive
https://www.inverse.com/article/58681-online-radicalization-hate-cluster-map

SciGlow.com
First of its kind mapping model tracks how hate spreads and adapts online
https://sciglow.com/other/first-of-its-kind-mapping-model-tracks-how-hate-spreads-and-adapts-online/

ABC (Spain)
Peor que un virus: descubren cómo se extiende el odio por las redes sociales
https://www.abc.es/ciencia/abci-peor-virus-descubren-como-extiende-odio-redes-sociales-201908211900_noticia.html?vca=rrss&vmc=abc-es&vso=tw&vli=cm-ciencia

ORF (Austria)
Mit Mathematik gegen Online-Hass
https://science.orf.at/stories/2990262/

Giornale di Sicilia (Italy)
Internet, creata la prima mappa che traccia la diffusione dell'odio online
https://gds.it/articoli/tecnologia/2019/08/21/internet-creata-la-prima-mappa-che-traccia-la-diffusione-dellodio-online-9d1d3029-38a7-48f5-8ec9-8d889dd59fbb/

Wissenschaft (Germany)
Social Media: Netzwerke des Hasses
https://www.wissenschaft.de/technik-digitales/social-media-netzwerke-des-hasses/

A **list of publications from the project** is as follows. To our knowledge, AFOSR support is stated in the offline/online documentation of all of these publications. In a few, a typo accidentally entered, meaning that the award was listed by the AFOSR proposal number 16RT0367, not the award number itself.

1. "To slow or not? Challenges in subsecond networks", Science 355, 801 (2017); Neil F. Johnson
2. "Using Competition to Control Congestion in Autonomous Drone Systems" Electronics 6, 31 (2017); Manrique, P.D.; Johnson, D.D.; Johnson, N.F.
3. "Stochastic modeling of possible pasts to illuminate future risk" Oxford Handbook of Complex Disaster Risks, Oxford University Press (to appear) 2017; Gordon Woo and Neil F. Johnson
4. "Atypical viral dynamics from transport through popular places" Phys. Rev. E 94, 022304 (2016); Pedro D. Manrique, Chen Xu, Pak Ming Hui, Neil F. Johnson
5. "Anomalous Contagion and Renormalization in Networks with Nodal Mobility" Europhysics Letters EPL 115, 18001 (2016); Pedro D. Manrique, Hong Qi, Minzhang Zheng, Chen Xu, Pak Ming Hui, Neil F. Johnson
6. "Open source data reveals connection between online and on-street protest activity" EPJ Data Science 5, 18 (2016); Hong Qi, Pedro Manrique, Daniela Johnson, Elvira Restrepo, Neil F. Johnson
7. "Association between Volume and Momentum of Online Searches and Real-World Collective Unrest" Results in Physics 6, 414 (2016); Hong Qi, Pedro Manrique, Daniela Johnson, Elvira Restrepo, Neil F. Johnson
8. "New online ecology of adversarial aggregates" Science 352, 1459 (2016); N. F. Johnson, M. Zheng, Y. Vorobyeva, A. Gabriel, H. Qi, N. Velasquez, P. Manrique, D. Johnson, E. Restrepo, C. Song, S. Wuchty
9. "Women's connectivity in extreme networks" Science Advances 2, e1501742 (2016); Pedro Manrique, Zhenfeng Cao, Andrew Gabriel, John Horgan, Paul Gill, Hong Qi, Elvira M. Restrepo, Daniela Johnson, Stefan Wuchty, Chaoming Song and Neil Johnson
10. "Quantum Hysteresis in Coupled Light-Matter Systems" Entropy 18, 319 (2016) doi:10.3390/e18090319; Fernando Gomez-Ruiz, Oscar Acevedo, Luis Quiroga, Ferney Rodriguez, Neil F. Johnson
11. "Exploiting non-trivial spatio-temporal correlations of thermal radiation for sunlight harvesting", J. Phys. B: At. Mol. Opt. Phys. 50, 124002 (2017); De Mendoza, Adriana; Caycedo-Soler, Felipe; Manrique, Pedro; Quiroga, Luis; Rodriguez, Ferney; Johnson
12. "Exploring the Effects of Photon Correlations from Thermal Sources on Bacterial Photosynthesis"

Results in Physics 6, 957 (2016); Pedro D. Manrique, Felipe Caycedo, Adriana De Mendoza, Ferney Rodriguez, Luis Quiroga, and Neil F. Johnson
13. “Hidden resilience and adaptive dynamics of the global online hate ecology”, Nature 573, 261 (2019); N. F. Johnson, R. Leahy, N. Johnson Restrepo, N. Velasquez, M. Zheng, P. Manrique, P. Devkota, S. Wuchty
14. "Emergent dynamics of extremes in a population driven by common information sources and new social media algorithms”, Scientific Reports 9, 11895 (2019); N. F. Johnson, P. Manrique, M. Zheng, Z. Cao, J. Botero, S. Huang, N. Aden, C. Song, J. Leady, N. Velasquez, E. M. Restrepo
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