Workshop of Scientific Evolutionary Writing

Complexity Science Hub Vienna
Josefstaedter Strasse 39
1080 Vienna

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COMPLEXITY
SCIENCE
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Aim and scope:

All scientific research involves attempts to resolve a mystery, overcome an obstacle or solve a problem. This makes them stories with narrative potential. But most scientific papers lack basic story-telling mechanisms. This workshop will explore story-telling techniques and how they can be used in scientific papers while maintaining the scientific rigour required for the world's top journals. Participants will be challenged to embark in an evolutionary process of their creations to rewrite and refine their texts till to a point in which "texts can only be worsened".

Write
About
Science
WAS

Organizers: Stefan Thurner and Verena Ahne
Sponsors: INSERM, Sony Computer Science Laboratories Paris, ANR, Complexity Hub Vienna

Your instructors...

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Workshop Programme

Day I

9:00 Introduction

9:15 Writing an Initial Draft

10:15 Coffee

10:45 Cognitive Elements of Communication I

12:15 Lunch

13:45 Editing as an Evolutionary Algorithm:
Selection and Exploration

14:30 Cognitive Elements of Communication II

15:15 Coffee

15:45 Editing Exercises

16:45 First Edit

18:00 End of Day I

Day II

9:00 Cognitive Elements of Communication III

9:30 The Process of Writing

10:00 Coffee

10:30 Second Editing Session

12:00 Lunch

13:30 Evolutionary Barriers and Opportunities

14:15 Third Editing Session

15:30 Coffee

16:00 Inflexion Points

16:30 Case Studies

17:30 Concluding Remarks and Discussion

18:00 Workshop ends

THIS WEEK

EDITORIALS

MOVIE-MAKING Screen techniques show how ancient amniote walked **p.266**

WORLD VIEW Payments for papers push professors to predatory journals **p.267**

MATHEMATICS Topology pioneer Michael Atiyah dies, aged 89 **p.271**

Super structures mimic metals

Concepts in metallurgy combine with 3D printing in an approach to designing strong, lightweight materials.

Astronauts on the International Space Station have had access to an orbiting 3D printer for several years now. But the real advances are being made down on the ground. The technology might be known among the public for turning out trinkets and expensive gifts, but steady progress is also being made in more challenging engineering applications.

Take the fabrication of complex network structures known as architected materials. These 3D structures can be carefully designed to achieve high strength-to-weight ratios compared with those of many conventional solid structures. They require less material than a fully solid structure to achieve similar performance capabilities, making them potentially resource-efficient. And the weight saving means that less energy is required to carry them about, making them intriguing for applications in which energy efficiency is a priority, such as prosthetics or aerospace technology. Such structures are, however, very difficult to fabricate using conventional techniques. And that is where 3D printing — also known as additive manufacturing — comes into play.

In this week's *Nature*, scientists at Imperial College London and the University of Sheffield, UK, report how they used 3D printers to create an unusual — and potentially very useful — series of architected materials by borrowing concepts from metallurgy (M.-S. Pham *et al. Nature* **565**, 305–311 (2019); see also page 303). They deliberately introduce what look like imperfections into 3D-printed plastic and metal lattices, to make them stronger. This strategy mimics on a larger scale the structural and compositional imperfections that can enhance the mechanical performance of normal crystalline materials: the lattice of the architected material stands in for the atomic arrangement in a crystal.

In one class of architected structure, the researchers created a material mimicking a polycrystalline structure — that is, one in which, instead of a single regular lattice structure, the material is broken up into 'metagrains' with different lattice orientations. Furthermore, they were able to tune the size of these regions to replicate a known effect in which mechanical strength is controlled by grain size. (In a standard polycrystalline metallic system, it is the boundaries between the grains that hinder material deformation.)

In another approach, the scientists mimicked a technique called precipitation hardening, often used in the manufacture of high-performance alloys. They also studied dual-phase lattices (mimicking steels). They speculate that 3D printing could be used to give structures the same kind of reversible stress-induced phase transformation as is seen in superelastic materials — a desirable property in cases where resilience to, and recovery from, deformation is required.

The authors explored three very different materials for their structures, requiring three different printing technologies. As expected, the properties of these materials were important. Further base materials could be investigated, and other mechanistic approaches for controlling properties are available. The parameter space for future exploration is large.

These demonstrations are just proof of principle; architected materials more generally are still a very new concept. Much work needs to be done before these ideas can be used widely. For example, researchers need to be able to make much larger structures, to exploit the breadth of available engineering materials and to develop design tools that can cater for the complexity of real-world applications.

But 3D printing more generally is now making genuine inroads in manufacturing. Industrial researchers have found additive manufacturing in metals to be appealing because it creates much less waste than does machining sections from a solid block; as such, it is now being used to mass-manufacture a few specific aerospace components. And US aerospace company GE Aviation says it has used additive manufacturing to improve weight efficiency in its new Affinity supersonic jet engine — scheduled to fly in 2023 — making supersonic travel that bit cheaper. As we wrote in a Toolbox article this month, it is also making inroads in the research laboratory (see *Nature* **565**, 123–124; 2019).

"It is said that 3D printing will be a key feature of the fourth industrial revolution."

It is sometimes said that 3D printing will be a key feature of the fourth industrial revolution, the era of big data, connectivity and human–machine integration. Metallurgy — specifically, developments in iron and steel manufacture — was central to the original Industrial Revolution. Metal endures. And now, architected materials enabled by metallurgical know-how and 3D printing could also go from strength to strength. ■

Screen time

How much is too much? An analysis tries to get to the bottom of a crucial question.

It has become a defining question of our age: do children and adolescents spend more time than is healthy staring at a phone, tablet or computer? Should parents limit their access? Should governments?

Nearly all US teenagers say they have access to a smartphone, and about half say they are online almost constantly, according to a 2018 Pew Research Center survey (see go.nature.com/2akajas). In the United Kingdom, the time young people spend online has almost doubled over the past decade, the communications-industry regulator, Ofcom, has found (see go.nature.com/2hd0c4p). Parental concerns about media use are rising, too — fuelled by headlines and political pronouncements. On 2 October 2018, Matt Hancock, UK secretary of state for health, issued an urgent warning, saying that the threat to children's mental health from social media is similar to that from sugar to their physical health.

In cases of such significant public concern, it often falls to the

Research Statement

The Development of Synthetic Organic/Organometallic Methods and Future Interests

Recently, a synthetic organic renaissance has changed the way we plan synthetic strategy. Governmental regulations demand cost minimization and reduction of hazardous waste streams. The use of enantiomerically pure drugs in chemotherapy is necessary not only to realize enhanced specificity, but also to avoid possible side-effects cause by the other enantiomer. Furthermore, the elucidation of biological processes through structure activity relationship (SAR) studies depends heavily on organic synthesis to identify clinical compounds and improve pharmacological profiles.

The development of synthetic methods that meet the regulatory and commercial needs of the chemical industry, especially pharmaceutical interests, requires the training of students in organic synthesis. In light of these requirements, my research program concentrates on transition metals as a means of achieving efficient and cost-effective organic synthesis.

The use of transition metals to effect a desired transformation has several advantages over classical organic methods. First of all, metals can effect reactions catalytically ultimately leading to reduced waste and more cost - effective syntheses. Second, enantioselective processes occurring on a metal center containing chiral ligands will afford enantiopure compounds. Finally, the mild and chemoselective reactivity of transition metals allows a more convergent approach to complex organic molecules without the need for cumbersome protection/ deprotection strategies. My current projects, and those I envision, develop novel synthetic methodologies using transition metals and examine their scope and limitations, the ultimate goal being the efficient and economical asymmetric synthesis of clinically interesting compounds.

Using the methodological studies described below as a foundation, I envision my program expanding into bioorganometallic chemistry as a method of achieving selective chemical transformations. For example, transition metal-catalyzed processes using ligands capable of molecular recognition should be useful as models for naturally occurring metalloenzymes. The design of peptide and carbohydrate based ligands that will impart selectivity as a result of distinctive molecular associations is an area with enormous potential and I present some of my initial interests toward this end in the last proposal of this section. This represents long - term research interests that will allow my group to use its knowledge of organic and organometallic synthesis to make valuable contributions to the field of bioorganometallic chemistry.

Income-based variation in Sustainable Development Goal interaction networks

Introduction

Many conflicts result from the way people interact with each other and with our planet. Since 1992, a range of global initiatives have emerged to find a more sustainable and equitable solution to these conflicts. In 2015, the United Nations set a 15-year plan, composed of 17 sustainable development goals and 169 associated targets, to promote prosperity for all while protecting our planet. Those goals touch on all aspects of human life and therefore interact in complex ways. These goals do not exist in isolation and synergies and conflicts can emerge from their interactions. For example traditional approaches to increasing agricultural productivity (SDG1) will lead to biodiversity and natural habitat loss therefore affecting our ability to meet SDG15.

The inter-dependencies of SDGs were recognised from their inception, but the effects of actions to achieve one goal on the ability to achieve others were anticipated only recently. Some work helped to highlight how interactions between SDG pairs can be negative or co-beneficial. However, in many instances the statistical approach limited the ability to make inferences relevant for interventions. One particular hurdle to date is the lack of recognition in these analytical approaches that interactions can and will vary depending on the socio-economic characteristics of countries. Accordingly, there is little knowledge of the context of the network emerging from direct and indirect interactions between SDGs and there are no robust inferences of associations between goals. This is important because efforts to meet SDGs in isolation can be counter-productive if they affect other SDGs negatively.

Not all interactions may be negative and investment in some SDGs can have additional benefits on multiple goals. There are also other barriers to SDG implementation, as the status quo on some goals can be advantageous for some groups (vested interests) or indeed desirable (for socioeconomic reasons). Understanding the SDG network can help to find new indirect ways to progress on specific SDGs while avoiding non-SDG barriers. Likewise, identifying indirect positive effects of SDGs on other goals can help define the best governance structures to capitalise on synergies and accelerate progress towards the 2030 targets. Finally, using a robust and unified approach to estimating direct and indirect interactions among goals can help us determine whether those interactions differ among countries, which could also explain diverging views on SDG interlinkages.

Studying the topology and drivers of networks has given us crucial insights about complex systems such as health, ecosystems, financial systems and our societies. Network theory provides analytical tools to determine how such mathematical representations of systems can evolve through time and how they might respond to perturbations. We apply a network approach to the SDGs in order to estimate what we call the sustainome, the system of SDG interactions. The sustainome can be represented as a network, where the vertices are the SDGs (goals or targets) and the edges are relationships between them. We estimate the sustainome the network of interactions at two scales: among the 169 SDG targets and among the 17 SDG themselves. The concept of the sustainome is inspired from the conceptual definition of sustainomics, defined as the study of how to achieve sustainability by maintaining six capitals – infrastructure, finance, communities, people, ecosystems, and biodiversity– while generating the flows we require from those capitals to achieve the SDGs.

Relationships among goals can be defined in a number of ways, from shared concepts in their definitions4 to dependencies in indicator trajectories. Within a sustainome framework, interactions between the SDGs are represented as the associations between progress towards each SDG (see Methods). For example, if initiatives are implemented to increase GDP, will they be associated with a degradation of biodiversity? Several organisations have monitored macroscale indicators associated with the SDGs in most countries over the past decades, which allows us to determine global interactions among the SDGs.

Exercise I Emphasising actors and actions

In each case, select the sentence below that focuses best on the actor and action

1.a) Scientific literature does not have to have boring qualities.
b) Scientific literature does not have to be boring.
c) Boring qualities are not always a part of scientific literature.

2. a) The focus of American philosophy is rugged individualism.
b) American philosophy is rugged individualism.
c) Rugged individualism is the focus of American philosophy.

3. a) The dominant social order, or the prevailing ideas of the time, challenges many popular science authors to think outside the box.
b) Challenging many popular science authors to think outside the box are the prevailing ideas of the time, or the dominant social order.
c) The consideration of the dominant social order, or the prevailing ideas of the time, challenges many popular science authors to think outside the box.

4. a) Over time, American society has come to value individuality.
b) Individuality in American society has over time become valued.
c) Over time, individuality has come to be valued by American society.

5. a) As early as 1832, Alexis de Tocqueville, in his book Democracy in America, wrote about the national desire for individualism.
b) As early as 1832, Alexis de Tocqueville wrote in his book, Democracy in America, about the national desire for individualism.
c) As early as 1832, the national desire for individualism was written about by Alexis de Tocqueville in his book, Democracy in America.
d) A national desire for individualism was observed as early as 1832 by Alexis de Tocqueville in his book, Democracy in America.

Exercise II

Revise the following sentences so that the subject and verb identify key actors and actions. There may be more than one possible answer.

Example
On 17 August 1942 , near the isolated desert crossroads of Freda, California, a camp was set up by seven men.
Sample answer:
On 17 August 1942, seven men set up a camp near the isolated desert crossroads of Freda, California.

1. The emergence of swine flu occurred in the US in 1998 and hog farms across North America have since found it to be endemic

2. Equipped with a suite of pig, bird and human genes, the evolution of swine virus has been happening rapidly.

3. Many animals are known to become infected with flu, including warterfowl, pigs and humans.

4. Were a pig to catch two kinds of flu at once, it could start to act as a mixing vessel, and it is possible for hybrids to emerge with genes from both viruses.

5. Few fossil traces were left by the very first animals.

6. A sketch of our great-to-the-nth grandmother is slowly being pieced together by evolutionary detectives by comparing the genes of living organisms and painstakingly working out family trees.

7. The confirmation of this close kinship comes from DNA sequence comparisons.

Exercise III

Write one short sentence capturing the main point or claim made by each of the following paragraphs. (Feel free to simply underline parts of the existing sentences if they already capture the main point or claim.)

The rise of biomathematics, which led John Maynard Smith to say, “if you can’t stand algebra keep out of evolutionary biology,” has been a runaway success. In many fields, empiricists continually struggle to keep up with and verify the assumptions and predictions of modellers.

An exception is the famously contentious topic of sympatric speciation — the process by which new species arise from coexisting as opposed to geographically isolated populations. There is growing evidence, particularly from lakes full of closely related fish species, that sympatric speciation does occur in nature. But models of the phenomenon have stubbornly concluded that evolution of sexual isolation without spatial isolation seems very unlikely.

At first glance, sympatric speciation looks straightforward. If a lake contains two potential resources — say, large or small prey — then large or small predatory fish will do well while medium-sized fish will be at a disadvantage. This disadvantage to intermediates, termed ‘disruptive selection’, creates pressure for divergence into two populations of distinct ecological types.

In sexual populations, the stumbling block preventing sympatric speciation is that mating between divergent ecotypes constantly scrambles gene combinations, creating organisms with intermediate phenotypes (physical characteristics). This mixing can be prevented only if there is assortative mating, in which pairings between similar individuals are more common. With disruptive selection, this pairing pattern is selectively favoured, because it reduces the production of offspring that are less well adapted to their environment. But there is a barrier to the evolution of assortative mating — recombination, the shuffling of genes during gamete formation, which means that genes for mating preference and ecotype (size for instance) may get mixed up whenever an occasional mating between different types occurs. This creates individuals with a preference for the opposite ecotype, increasing gene flow between types and opposing speciation.

Exercise IV on topic sentences

Choose the best among the several topic sentences listed for each paragraph below.

1. The strictest military discipline imaginable is still looser than that prevailing in the average assembly-line. The soldier, at worst, is still able to exercise the highest conceivable functions of freedom -- that is, he or she is permitted to steal and to kill. No discipline prevailing in peace gives him or her anything remotely resembling this. The soldier is, in war, in the position of a free adult; in peace he or she is almost always in the position of a child. In war all things are excused by success, even violations of discipline. In peace, speaking generally, success is inconceivable except as a function of discipline.
a. Soldiers need discipline.
b. We commonly look on the discipline of war as vastly more rigid than any discipline necessary in time of peace, but this is an error.
c. Although soldiers are not always disciplined, they serve an important social function in wartime.
d. In times of peace, soldiers often convert easily from wartime pursuits to the discipline necessary successfully to compete in even the most competitive marketplace.

2. Indeed, quantitative records of many different kinds of human activity are already being gathered and stored in enormous databases. E-mail and phone records document our social and professional interactions; travel records and GPS navigation systems capture our travel patterns and physical locations; credit-card companies maintain records of our shopping and entertainment habits. Although in the wrong hands, these data sets could represent Orwellian tools of power, for scientists they offer incredible insights into human behaviour. Combine this capability with the sophisticated tools of network theory, which analyzes relations between millions of individuals, and you get a glimpse of an unprecedented opportunity to quantify human dynamics.
a. The gathering of email data by large corporations represents a threat to privacy.
b. Human behaviour cannot be captured in simple or even complex mathematical models.
c. Modern technology is rapidly establishing the tools for a mathematical understanding of a great deal of human behaviour.
d. Social science had not yet reached the level of sophistication of the natural sciences.

3. In Montreal, a flashing red traffic light instructs drivers to careen even more wildly through intersections heavily populated with pedestrians and oncoming vehicles. In startling contrast, an amber light in Calgary warns drivers to scream to a halt on the off chance that there might be a pedestrian within 500 meters who might consider crossing at some unspecified time within the current day. In my home town in New Brunswick, finally, traffic lights (along with painted lines and posted speed limits) do not apply to tractors, all terrain vehicles, or pickup trucks, which together account for most vehicles on the road. In fact, were any observant Canadian dropped from an alien space vessel at an unspecified intersection anywhere in this vast land, he or she could almost certainly orient him-or-herself according to the surrounding traffic patterns.
a. People in Calgary are careful of pedestrians.
b. Although the interpretation of traffic signals may seem highly standardized, close observation reveals regional variations across this country, distinguishing the East Coast from Central Canada and the West as surely as dominant dialects or political inclinations.
c. People in Montreal drive faster than people in Alberta, and Maritimers generally don’t pay any attention to traffic signals at all.
d. Canadians do not follow traffic signals properly.

Abstract Exercise

In recent years, some effectiveness of radio frequency-based (also known as “microwave-based”) catalyst state diagnosis for diesel engines has been shown. This work has focused and aimed mainly on SCR systems. To increase the efficiency of exhaust after-treatment systems, SCR catalysts can also be put together in combination with NO_X storage catalysts (NSC). It has been widely noted that, for optimum performance, the degree of loading of the storage components has to be monitored. Technical challenges have not completely avoided or hampered progress, but heretofore, and until the present moment in time, in commercial application this has been done indirectly by using mathematical models. In this paper, the opportunities of a simple radio frequency (RF) based method for a direct determination are highlighted. Therefore, a commercial NSC was investigated between 210 and 390 °C. A linear dependence between the RF signals and the stored amount of NO_X was found. It is worth pointing out that the NO_X and oxygen gas concentrations do not directly affect the RF parameters, but they have an indirect influence. By evaluating multiple RF signals, which are based on different material effects, a separate determination of the oxygen and NO_X storage level is suggested.

Diesel Emissions Reduction Fact Sheet

All of the following information should appear in the abstract in some form

What is SCR? Selective Catalytic Reduction (SCR) is an emissions reducing technology that injects a liquid-reductant agent into the exhaust stream of a diesel engine. It uses catalysed reactions to cut NO and NO_2 (together denoted NOx) emissions by 90 per cent.

What is NSC? Emissions can be further eliminated using so-called NOx storage catalysts (NSC), which store and release NOx cyclically during distinct phases of engine operation. NSC processes the exhaust before it is fed to the SCR.

Optimal performance of combined SCR/NSC systems requires what? Accurate monitoring of the NSC absorbed NOx loads.

How is monitoring done now? With mathematical models, and not very accurately. **This is the problem to be overcome**

What is a possible alternative? To measure loads directly and continuously using radio frequency (RF) signals.

How does the measurement work? The RF transmission properties of the NOx catalyst vary with the degree of NOx loading

What does this work do? Demonstrates that RF signals give good measurements of NOx loads

Significance of temperature range 210-390 °C? This is the typical NSC operating range.

Further finding: Prevailing NOx and oxygen gas concentrations do not interfere with accurate determination of the stored NOx amount, as they did not directly alter the RF parameters.

Further finding: Using multiple RF signals makes it possible to simultaneously monitor the NSC storage level of oxygen, in addition to NOx.

Simplify the sentences in this paragraph:

I am 6 years old and the bell rings for recess on my first day at school causing all my classmates to run gleefully away. But unlike them I cannot see, at least not with my eyes, and instead, I click my tongue, listening for echoes from the wall to my left, walking with my hands slightly outstretched to keep me from running into chairs that may have been left askew. I hear kids laughing and shouting through the open door and, by clicking, I also hear the presence of the sides of the doorway in front of me as I go through it to the playground for the first time. After a few steps, I stop to listen, standing on a crack in the pavement that runs parallel to the building behind me and then click my tongue loudly and turn my head from side to side, noticing that the way is open, shot through with scurrying voices and shoes scampering to and fro. What is around me, how do I get there and how do I get back?

Find a shorter way to write the following phrases:

At all times .....

At the present time .....

In today's society .....

At this point in time .....

Because of the fact that .....

For the purpose of .....

In order to .....

Until such time as .....

For the reason that .....

Due to the fact that .....

In the event that .....

By virtue of the fact that .....

By means of .....

In the final analysis .....

It is worth pointing
out in this context that .....

It is significant to note the fact that .....

Found to be .....

It is plainly demonstrable from
the data presented in Table 2 .....

Needless to say .....

Poor paragraph

Improve the following paragraph by
1. Add a clear topic sentence, either by writing a new one, or by finding the sentence buried in the text which should be the topic sentence.

2. Simplifying the language and eliminating wasted words.

People can and do perish from random accidents, of course, but if we leave that to one side for the moment, a more usual problem arises from the daily environmental insults of life which may – in a wear-and-tear hypothesis – eventually destroy the bodily capabilities of ongoing human life, leading to death. The myriad, diverse and often clever supporters of the wear-and-tear theory maintain, for example, that the very practice of breathing causes us to age because inhaled oxygen produces toxic by-products. Of course, we must all die some day, in pain or otherwise, at home or elsewhere. If asked why, however, it is found that people broadly adhere to a couple of interesting and broad theoretical conceptions concerning what triggers a human's inevitable decline to death, with wear-and-tear being only one such notion. Perhaps instead, others conjecture, we could have some kind of functioning internal clock which is genetically programmed to run down. This is a second competing theory. Advocates of the internal clock theory believe that individual cells are told to stop dividing and thus eventually to die by, for example, hormones produced by the brain or by their own genes.

Most of the farmers are extremely poor. Attracted by cheap loans from pesticides traders and the prospect of a quick buck, they borrowed heavily to raise cotton on small plots of land.

According to the Ministry of Agriculture, the crop losses and destruction in Andhra Pradesh arose from the repeated application of excessive amounts of chemicals - a practice actively encouraged by pesticides traders.

The suicide of Samala Mallaiah in Nagara village grabbed media headlines. He owned one acre of land, leased two more and grew cotton on all three. After making a loss in the first year, he leased yet more land in an attempt to recover. Confronted with falling prices, mounting debts and pest attacks, he committed *harakiri.* 'Cotton has given us shattered dreams,' said one old farmer in Nagara village.

As many as 60,000 small farmers in the region of Andhra Pradesh, southern India, have taken to farming cotton instead of food crops. Some 20 of them have recently committed suicide by eating lethal doses of pesticide.

Whitefly, boll weevils and caterpillars multiplied and destroyed their crops, despite the constant application of pesticides. The average yield of cotton fields in Andhra Pradesh fell by more than half in just one year. Now the farmers are in no position to repay the loans or feed their families.

Nearly half the pesticides used in India go into protecting cotton, the most important commercial crop in the country. However, pests have shown increased immunity to a range of pesticides. Last year there were heavy crop losses due to leaf-curl, which is caused by the dreaded whitefly. This nondescript, milky-white fly sucks sap from the cotton leaves, making them curl and dry up. The fly struck first in Pakistan and north-western India. Then it turned south.

Space Junk is Now a Clear and Present Danger

Last Saturday, the National Aeronautics and Space Administration launched the Ice, Cloud and Land Elevation Satellite-2, which will monitor Earth's ice sheets, recording changes in ice thickness as small as half a centimeter. The satellite will allow us to see one consequence of our collective pressure on the planet's environment. And yet it will, in a small way, also exacerbate another emerging global problem.

The U.S. Strategic Command is already actively tracking more than 20,000 satellites, rocket pieces and collision fragments bigger than a softball that are orbiting the earth, which together present a looming menace to satellite operations and everything that depends on them, including global positioning systems, telecommunications, weather forecasts and the internet. Over 50 years ago, when we first started putting satellites in orbit, we seemed small, and the earth very big. Now, with nearly 500 new satellites going up every year, our influence is no longer small.

Congested space is another reflection of our entry into the Anthropocene — a new era of history in which everything about the earth and its climate, even the space around it, is profoundly affected by human activity.

NASA scientists began thinking about potential space overcrowding in the early 1970s, when the number of satellites in orbit was approaching 4,000. In an influential paper, space scientists Donald Kessler and Burton Cour-Palais made a rough estimate that, as the number of satellites grew, the risk of collisions would become an issue by the 2000s. They weren't far off. In 2009, a U.S. commercial satellite collided with an inactive Russian communications satellite at a speed of some 26,000 miles per hour, creating two clouds of debris that rapidly dispersed throughout low Earth orbits, at anywhere from 400 to 1,000 miles above the earth.

More important, Kessler and Cour-Palais also pointed to a serious risk that would arise if the number of objects in low or medium Earth orbits became too high: A higher density of objects, they argued, makes it more likely that the secondary fragments created in one collision will in turn strike other objects. A sufficient density of debris could set the stage for a fragmentary chain reaction that could quickly render the entire space around Earth unusable.

Space scientist Carolin Frueh of Purdue University told me by email that while this analysis depends on many assumptions, some of which are debatable, "It seems to be beyond doubt that an increased space population leads to this effect."

Incredibly, scientists now think we're getting close to this critical stage, and that we urgently need to clean it up. There are lots of ideas being pursued by researchers who think of themselves as "space environmentalists." This past weekend, a satellite launched in June began testing a technique to throw a net over pieces of space debris and pull them into trajectories that would lead to their burning up after atmospheric re-entry. That kind of approach might work on some of the largest objects, but researchers have other ideas for the smaller ones, such as employing the subtle periodic forcings of the sun and moon to gradually steer debris on easy pathways toward atmospheric re-entry.

Given the stakes, and human ingenuity, the chances are high that we'll avoid the fragmentary catastrophe, which space scientists call the Kessler syndrome. But it's certain that we've moved into a management era of near-Earth space. A space that even a few decades ago seemed unfathomably vast has become subject to perpetual monitoring and management, just so we can go on using it. The need for intense management will only grow if companies such as Boeing Co., OneWeb Satellites and SpaceX go on to deploy thousands of new satellites over the next decade or two.

The notion of the Anthropocene has generated some controversy, in part over the difficulty of deciding on when it began but also how it reflects a new geological phase of Earth history. But there's no question that we've entered a profoundly distinct phase, with people having modified over 50 percent of the earth's surface, generating geophysical flows of nitrogen and phosphorous larger than natural processes produce and dispersing plastic waste to every corner of the oceans.

Now add to that the very edge of space — already under perpetual human management.

FURTHER READING

How to Write and Illustrate a Scientific Paper
Björn Gustavii
Cambridge University Press
ISBN 9780521703932

The Little, Brown Handbook
J Aaron and H Fowler
Pearson Longman
ISBN 0321389514

The Science of Scientific Writing
George D Gopen and Judith A Swan
American Scientist, November-December, 1990

The Magical number seven, plus or minus two
GA Miller Psychological Review Vol. 101, No. 2, 343-352
https://bit.ly/1MOGG4o

The Visual Display of Quantitative Information
Edward Tufte
Graphics Press USA
ISBN 9780961392147