Getting the most out of maths: How to coordinate mathematical modelling research to support a pandemic, lessons learnt from COVID-19

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Abstract

In March 2020 mathematics took centre stage in the fight against the COVID-19 pandemic. Mathematical and statistical modelling provided critical information on the spread of the virus and the potential impact of different interventions. The unprecedented scale of the challenge led the relatively small epidemic modelling community in the UK to be pushed to its limits. At the same time, mathematical modellers across the country were keen to use their knowledge and skills to support the COVID-19 modelling effort. However, this sudden great interest in epidemic modelling needed to be coordinated to provide much-needed support, and to limit the burden on epidemic modellers already very stretched for time. In this paper we describe three initiatives set up in the UK in spring 2020 to coordinate the mathematical and wider science research communities in supporting mathematical modelling of COVID-19. Each initiative had different primary aims and worked to maximise synergies between the various

projects. We reflect on the lessons learnt, highlighting the key roles of pre-existing research collaborations and focal centres of coordination in contributing to the success of these initiatives. We conclude with recommendations about important ways in which the scientific research community could be better prepared for future pandemics.

Section 1: Introduction

From the beginning of the COVID-19 pandemic, mathematical modelling was a cornerstone of the scientific advice provided to governments, both in the UK and internationally. In the early days of the pandemic, data on infections were sparse and scientists were still learning about the characteristics of this novel virus. Mathematical modelling provided a powerful framework to synthesise many different (often limited and poor quality) data sources, providing a glimpse into potential futures under different scenarios. In the UK, outputs from mathematical models were frequently shown during the government official briefings to the public, as senior scientific advisors used modelling insights to explain to the general public why certain control measures were needed.

In the UK, the Government's Department for Health and Social Care (DSHC) was aware of the value and utility of mathematical models, and already had a group of experts in the form of the Scientific Pandemic Influenza Group for Modelling (SPI-M) which quickly moved to operational mode at the start of the pandemic and reported to the Scientific Advisory Group for Emergencies (SAGE). However, this group of experts was relatively small, and with a very focused set of expertise which did not fully cover the breadth needed for the unprecedented response to the pandemic emergency. As a result, SPI-M was quickly pushed to its limit by the unprecedented need for modelling input to inform the UKs response to the pandemic as it began to unfold in the first half of 2020.

At the same time, mathematical modellers across the country were keen to use their skills to support the COVID-19 modelling effort. Many mathematicians, statisticians and other scientists saw the potential for their areas of expertise to strengthen the work of epidemic modellers on the front line, ensuring that the most cutting-edge and state-of-the-art methods and approaches were being used to inform government decision making.

This explosion of interest in the field of epidemic modelling led to a sudden flurry of preprints on modelling studies about various aspects of the pandemic(Fraser et al., 2021; Majumder and Mandl, 2020), as well as an influx of communications to leading epidemic modelling experts from academics new to the area and keen to establish collaborations. The expertise of these academics ranged from those who were adjacent to the areas under study (e.g. modelling of animal diseases, network theory), through those with broader related expertise (e.g. uncertainty quantification, urban analytics) to those with no related expertise. While well-meaning, this newfound interest in the field put huge pressure on epidemic modellers who were already extremely stretched for time. There were not enough experts to review papers and many potentially useful inputs from other fields were easily lost amongst the noise. Gog(Gog, n.d.) highlighted a number of ways in which scientists could use their skills to best support the real-time research during the pandemic. There was a clear need to

coordinate this sudden interest in epidemiology to ensure support was provided where it would have maximum benefit, without adding to the burdens of the epidemiological modelling community.

In this paper, we describe three initiatives that sought to address the challenge of coordinating the wider research interest so as to enhance the UK's capacity to provide mathematical modelling research to support scientific advice to the government. Each initiative had different and complementary aims, focused on engagement with particular communities of researchers and used different structures to coordinate activities. We reflect on the key roles that pre-existing collaborations and focused activities had in the success of these initiatives. Furthermore, we discuss the fundamental role that research institutes and organisations played in providing the infrastructure, professional services staff and overview of the research landscape, that enabled these initiatives to be undertaken in a timely manner and ultimately increased their positive impact.

Section 2: Coordination Activities at the beginning of the Pandemic in the UK

In this section we describe three initiatives in the UK that were set up between March and May 2020 to coordinate mathematical modelling research in support of the pandemic response. As the pandemic continued, further initiatives were set up through the second half of 2020 and into 2021, with many in the UK supported by UKRI emergency response grants, and we will briefly mention some of these in the conclusion. We provide here a brief overview of the principal aims of the initiatives, the main research communities involved and the primary activities that were undertaken.

Section 2.1 Virtual Forum for Knowledge Exchange in the Mathematical Sciences (V-KEMS)

In March 2020, the International Centre for Mathematical Sciences (ICMS), Isaac Newton Institute (INI), Newton Gateway to Mathematics and the Knowledge Transfer Network (KTN) working with various representatives from the mathematical sciences community convened the Virtual Forum for Knowledge Exchange in the Mathematical Sciences (V-KEMS)("https://www.vkemsuk.org," n.d.). This truly virtual organisation was brought into being by the force of collective will, with the aim of channelling the outpouring of energy and obvious desire of mathematical scientists from fields other than epidemiology to do something to ease the knock-on consequences of the pandemic.

V-KEMS has developed a range of virtual approaches to help address challenges from business and industry, government, the third sector, and other groups outside academia. These challenges may be long-standing or may have arisen directly as a consequence of disruption to UK society caused by the COVID-19 pandemic. V-KEMS' main focus is on identifying fruitful areas for input from the broader mathematical sciences community, notably including extensive engagement from operational researchers and from pure mathematicians as well as mainstream applied mathematicians and statisticians. Examples included tackling issues proposed by a network of stakeholders regarding the consequences of the pandemic, such as food supply and logistics, COVID safe train travel and mitigating

NHS waiting lists. In addition, V-KEMS has provided support to existing initiatives such as discussion fora and town hall meetings.

V-KEMS' delivery mechanisms include Virtual Study Groups (VSGs), webinars and the formation of virtual teams of mathematicians to meet with stakeholders to help frame questions in ways maximum benefit could be obtained from the mathematical sciences Where industry, business, government or the third sector have identified a quantitative or logistical problem that would benefit from mathematical input (such as physics-based modelling, statistics, data analysis or operational research), V-KEMS has facilitated this by putting the organisation in contact with relevant individuals or teams from the mathematical sciences community who can undertake a scoping or 'triaging' process. V-KEMS has also been able to provide the infrastructure and resources to host such meetings online.

However, V-KEMS' signature activity has been the development and delivery of VSGs, a number of which have fed directly into advice being developed by officials who have been working with Government in response to COVID-19. For example, the Unlocking Higher Education Spaces VSG provided input to dialogue between the Department for Education, the Department of Health and Social Care, Universities UK, the Scottish Government and the Welsh Government. Other activity has contributed to advice going to SAGE and SPI-M.

Other VSGs have helped to model and propose potential solutions to pre-pandemic problems or those that have been exacerbated because of the pandemic. One explored how the mathematical sciences could provide support in forecasting demand for surplus food products in the early stages of the pandemic, to ensure that a foodbank-related charity was well maintained by the food supply chain. Another looked at how to reduce the risk of COVID-19 transmission on trains by modelling scenarios looking at airflow, passenger movement and travel scheduling. A further VSG explored the challenges related to the delays in seeking and gaining access to cardiovascular treatment caused by the COVID-19 pandemic and the impact this will have upon hospital waiting lists. A VSG even provided important COVID-19 safety data for the Edinburgh Fringe Festival.

Over 1,600 attendees have participated in the VSGs since 2020, with 54% from a mathematical discipline, 20% from another academic discipline, 12% from industry and the rest from Government and other sectors. Whilst a VSG typically only lasts for three days, V-KEMs has paid great attention to following up the work done within them with relevant end-users, and in producing reports very rapidly afterwards. The results of VSGs have been used to inform policy makers and have been disseminated to a wide range of audiences through a variety of routes including journals, articles and podcasts. Many V-KEMS activities have also led to longer term mathematical sciences engagement with end-users and to the development of new mathematical ideas.

Section 2.2 Rapid Assistance in Modelling the Pandemic (RAMP)

The Royal Society, as the UK's national science academy, was involved from the very beginning of the pandemic response. It convened experts rapidly to provide timely advice and evidence on a range of topics, from face coverings to vaccines, through its Science in Emergencies Tasking Covid-19 group (SET- C). It set up the DELVE: Data Evaluation and

Learning for Viral Epidemics group, to support a data-driven approach to learning from the strategies taken by different countries to manage the pandemic. It also convened the RAPID Assistance in Modelling the Pandemic (RAMP) initiative to provide additional modelling support to SPI-M.

The RAMP initiative brought volunteers with modelling expertise from a diverse range of disciplines to support the epidemiological modelling community already working on COVID-19. The initial call went out at the very beginning of the pandemic response and the reaction from the academic community was far greater than any of the organisers had been expecting. Over 2000 individuals and teams came forward with an offer to help, with 500 of these coming from outside of academia, including the energy sector, finance, engineering firms, retail, travel and technology.

The RAMP initiative had three different elements. Firstly, the group embedded volunteers within existing research groups to provide immediate support to those providing scientific advice for government. These volunteers were carefully chosen to match the expertise currently missing or where additional support was needed.

Secondly, the groups established new research teams on areas that while perhaps not of immediate priority in March 2020, were identified as being key areas that could support the longer-term modelling of the pandemic. These areas included human dynamics in small spaces, the relationships between urban analytics and epidemiology, indoor transmission, within-host dynamics, structured expert judgement and comorbidities. The volunteers in these areas then connected with the epidemic modelling community through the Infectious Dynamics of Pandemics research programme (see Section 2.3 for more details).

Finally, RAMP established a Rapid Review Group (RRG, with over 100 reviewers signed up) to provide rapid assessments of the unprecedented volume of emerging research, identifying studies that were important for policy and evaluating their quality, to assist UK government and its advisory groups. The RRG primarily consisted of a team of expert modellers who provided rapid reviews of epidemiological modelling analyses. The RRG's team of reviewers were sent modelling analyses to review by UK government advisory groups (SAGE and SPI-M) and UK government departments. These analyses were usually publicly available preprints that were deemed to have potential implications for policy, but also sometimes included bespoke analyses that had been conducted. The RRG would then review the analyses, often within 24-48 hours, assessing them for their reliability and their likely relevance for current policy. The RRG would then set out their evaluation, and summarise the key assumptions and conclusions of the analyses, in a condensed format that was straightforward for government advisors to read. The activities of the RRG were supported by a discussion forum with over 550 members that helped to identify and scrutinise emerging research papers from around the world.

After the first wave of volunteer responses came to an end, the RAMP Continuity Network (a UKRI funded project) was established. Between January 2021 and June 2022, the network delivered a series of virtual and in-person meetings, workshops and virtual study groups, most of which were organised and run by the Newton Gateway to Mathematics in close partnership with the rest of the V-KEMS team. These events maintained strong

communication links among RAMP-initiated projects and further developed links across the wider modelling community around COVID-19.

Section 2.3 Infectious Dynamics of Pandemic Research Programme

On 5th May 2020, the Infectious Dynamics of Pandemics (IDP) programme began at the Isaac Newton Institute (INI) for Mathematical Sciences. INI is a visitor research institute based in the UK that runs research programmes on selected themes in the mathematical sciences, convening international experts to engage in research over an extended period of time. INI programmes are renowned for encouraging and supporting new collaborations, the exchange of expertise and ideas which are catalysed through lectures, seminars and informal interaction. Due to the restrictions on social movement in place within the UK and globally at the time, the IDP programme was run entirely virtually, the first of its kind at INI. The aims of the programme were three-fold: to provide additional capacity for the rapid assessment of strategies of immediate policy relevance; to provide a forum for mathematical modellers working to advise government bodies to connect with the wider research community internationally; to provide space for longer-term thinking about the challenges of understanding the dynamics of this particular pandemic and to identify lessons learnt for the future.

IDP built on two previous programmes held at INI on the topic of infectious disease modelling: Epidemic Models (held in 1993) and Infectious Dynamics of Diseases (IDD held in 2013 with a follow-up in 2014). This was reflected in its academic organising committee, with four of the ten organisers being co-organisers of the 2013 programme, while a fifth was a programme participant, and two being co-organisers of the original programme in 1993.

Over 100 researchers were invited to be participants on the IDP programme, from all career stages, in the UK and internationally. While INI programmes often have this number of participants in total over a 6 month period, IDP was unusual in that there were over 100 participants simultaneously for the entire duration of the programme. This reflected the fact that participants attended virtually and so there was not the usual limitation of physical space. The large number of participants also reflected the fact that this programme was ambitiously bringing together researchers from a number of different scientific communities as well as adapting to the shifting research landscape in response to the pandemic. The core invited participants were made up of those who had attended the 2013/2014 IDD programme but also included the leads on the RAMP initiated small projects, academic organisers of V-KEMS and researchers from wider mathematical sciences areas such as uncertainty quantification. Interestingly, of the invited participants who had not been part of IDD, many of them already had a connection with INI having been programme participants on other research programmes at INI (including, most recently, the 2016 programme on Theoretical Foundations of Statistical Analysis (SNA)(“https://www.newton.ac.uk/event/sna/,” n.d.), and the 2018 programme on Uncertainty Quantification for Complex Systems: Theory and Methodologies (UNQ) (“https://www.newton.ac.uk/event/unq/,” n.d.)). The established link that many researchers had with INI made it easier to engage with the different communities. INI also provided a neutral and trusted environment for engaging in rigorous academic debate. In addition to the invited programme participants, other researchers were

able to take part in the programme through the number of workshops that ran throughout its duration.

As with typical INI programmes, regular workshops and seminars made up the bulk of the activities that took place. For physical in person programmes, there is no need to organise informal discussion and networking sessions as these occur naturally in the communal areas within INI, but translating this informal *ad-hoc* discussion to the virtual environment took more curation. Therefore, in addition to workshops and seminars, there were also many scheduled discussion sessions on specific topics, and these worked best when there was either a specific planned outcome from the discussion session (e.g. a list of recommendations or a draft manuscript) or where someone presented slides to guide the discussion. Talks were recorded and made available on the INI website and YouTube channel to enable participation in the programme when was most convenient, especially in light of the fact that many were juggling other responsibility as well as joining across a range of time zones. These recorded talks, including a number from experts central to the pandemic response both in the UK and internationally, provided access very early on to the wider public on the mathematical modelling that was being used to provide government advice. For example, the plenary talk by Professor Graham Medley who was the chair of SPI-M at the start of the IDP programme was referenced in a UK national broadsheet newspaper (Rhys Blakely, 2020).

In keeping with the its aims (responsive, connecting to the wider mathematical modelling community, taking a long-term view), the topics covered throughout the programme broadly split into the following three areas. Firstly, the responsive activities, often organised in a matter of days, were directed by those on the programme organising committee who also sat on UK government advisory committees and focused on topics of immediate relevance to COVID-19. These included modelling for an exit strategy from lockdown, contact tracing and lessons from other diseases, COVID-19 and higher education and, finally, how the R value is estimated and its limitations as an epidemiological metric. The outcomes of these workshops and discussion sessions were both recommendations and reports sent to government advisory groups (Enright et al., 2021; *Recommendations for Augmenting Contact Tracing in the UK: Learning from Other Diseases*, 2020) as well as peer-reviewed academic papers (Thompson et al., 2021; Vegvari et al., n.d.).

Second, the IDP programme provided a forum for the RAMP-initiated projects (New Epidemic Models; Urban Analytics Approaches; Human Dynamics in Small Spaces; Within-Host Modelling; Comorbidities; Environmental and Aerosol Transmission; and Structured Expert Judgement) to initiate academic dialogue with the epidemic modelling community. These sessions provided academics new to the field the opportunity to discuss the current state of the art in epidemic modelling and where these new methods potentially could be of most benefit. These sessions were key in providing a forum for academic discussion and debate, allowing approaches to be questioned and enabling the identification of areas where additional mathematical support was most needed.

The later part of the IDP programme provided a chance to take a step back and to think about the longer-term implications of the COVID-19 experience with regards to future pandemics. The final workshop, ‘Future Pandemics’ aimed to bring together the diverse topics covered to reflect on what we can learn from the COVID-19 pandemic and how we

can be better prepared for future pandemics. The workshop covered the following areas: the emergence of new diseases; tackling new diseases; the wider context. Following on from this workshop, working groups were set up to focus on challenges for future pandemics in ten key areas: human-wildlife interface, emergence, elimination versus endemicity, interventions, vaccinations, inference, modelling, data, economics and policy. The outcome of these working groups led to a special issue about the Challenges for Future Pandemics in the journal *Epidemics* ("https://www.sciencedirect.com/journal/epidemics/special-issue/10DM7ZPJKM9," n.d.).

Section 3. Lessons Learnt

Section 3.1 The Power of Existing Collaborations and Networks

One of the key elements that enabled all three initiatives to succeed was that they leveraged and built upon existing collaborations and research networks. For example, V-KEMS developed virtual versions of existing knowledge exchange formats such as study groups with industry, and leveraged pre-existing links with government departments and industry through the KTN, Newton Gateway and knowledge exchange team at ICMS. It was also able to quickly tap into a pre-existing pool of researchers (i.e. participants on previous study groups with industry) who were interested in applying mathematical approaches to answer specific problems from industry and government.

Similarly, IDP used the strong collaborations, both within the UK and internationally, that had developed through the previous research programmes at INI on infectious disease modelling. These pre-existing links meant the INI was uniquely placed to mobilise rapidly the wider epidemiology research community both in the UK and internationally. In particular, the IDP programme provided a way for SPI-M modellers to engage with the wider epidemic modelling community on issues of highest priority. For example, as the UK was considering exit strategies from the lockdown that began in March 2020, it was clear that contact tracing was going to be a key part of this. Yet many questions remained about how contact tracing systems would work and what would ensure they were successful. In a matter of days, the professional services staff at INI, under the guidance of the IDP academic organisers, put together a workshop on contact tracing and what can be learnt from other diseases. This led to a set of recommendations (*Recommendations for Augmenting Contact Tracing in the UK: Learning from Other Diseases*, 2020) published on the INI preprint server that was then fed into scientific advice through IDP participants who were also members of SPI-M and SAGE.

One of the greatest challenges that the three initiatives faced was in trying to develop new collaborations between epidemic modellers, particularly those who were advising government directly, and those in the wider mathematical modelling and mathematical sciences community whose areas of expertise could provide helpful support. This was in part because the pressures of the real-time pandemic response did not provide the space needed to develop strong academic collaborations. Also, the virtual environment is not an ideal way for academics to work together on challenging maths problems and develop new interdisciplinary collaborations. As noted in section 2.3, the informal discussion and networking sessions that naturally occur in the communal areas within INI did not translate

well to the virtual environment. These *ad-hoc* discussions are frequently where the seeds are sown for novel ideas, and fruitful long-lasting academic friendships begun. Therefore, while the virtual environment provides a crucial way to widen participation to groups who may not be able to attend an event in person, it is important to remember the value of in person meetings in the development of strong academic collaborations.

Section 3.2 Centres of Coordination were key

All initiatives heavily relied upon the pre-existing infrastructure provided by research and coordination centres, namely ICMS, INI and the Royal Society. These centres were vital as they provided the teams of professional support staff that enabled the activities to be coordinated and organised in a timely manner.

For example, the expertise within the IT services team at INI was critical in identifying appropriate technologies to run webinars, virtual meetings and facilitate informal interactions and discussions between participants on the IDP programme. Furthermore, they were able to provide technical support to record meetings, which was important as many participants were not able to watch talks live. The INI professional services team ensured meetings were set up in a timely manner and communicated to programme participants, which was done primarily through a weekly bulletin containing all meeting links. All of this technical and administration support was indispensable in making sure the programme was set up quickly and that events were responsive to the needs of the researchers, allowing them to focus on undertaking the research.

V-KEMS too relied heavily on the events management staff's time to set up and run the Zoom meetings and was indebted to KTN, ICMS and INI staff's talents in designing online collaboration spaces and events using environments such as Mural and Sococo. The networks with industry through the Newton Gateway, KTN and the knowledge exchange team at ICMS were critical for identifying key problems within industry and government and providing a space for these end-users to connect with researchers in the mathematical sciences.

Section 3.3 Building collaborations around focused activities

Workshops and seminar series are tried and tested mechanisms within academia for building and developing new collaborations. Such events provide time and space to present ideas from diverse fields, discuss and challenge approaches and build trust between different research communities. The challenge during the pandemic was that the huge pressures on many scientists did not leave time to attend talks on topics and discussion that, while of interest, were exploratory and therefore not always of immediate benefit. Focusing activities around more specific areas of direct policy relevance, rather than academic topics of interest, was found to be a successful time-efficient way of facilitating new collaborations.

The new academic collaborations that developed around the topic of COVID-19 and higher education was an example of this. Work started as a V-KEMS virtual study group, with problems presented by the Department for Education as well as various universities in the UK around the potential challenges of reopening higher education institutions in the autumn

of 2020. This led to a workshop at IDP on COVID-19 and higher education which included talks by participants of V-KEMS, Department for Education, Universities UK and members of SPI-M who were involved in modelling work looking at the potential impact of reopening universities.

IDP participants who were also members of SPI-M were aware that there was likely to be an 'ask' from the government surrounding the potential impact of reopening higher education settings. This was also an area in which few SPI-M groups were actively working on. Therefore, following on from the V-KEMS and IDP activities, a working group of academics from within SPI-M and the wider modelling community, run through INI, met on a regular basis from autumn term of 2020 right through until spring 2022. The purpose of this group was to prepare proactively long before there was a specific 'ask' from government around the impact of COVID-19. By combining a number of smaller contributions from participants together, this working group provided key inputs into scientific advice in Jan 2021 centred around the reopening of higher education facilities following the Christmas holidays and the emergence of the alpha variant in the UK (Enright et al., 2022, 2021). This combined effort provided one of the few pieces of mathematical modelling evidence presented to SAGE in Jan 2021 about the potential impact of different measures regarding the reopening of higher education institutions, exemplifying where the coordinated activities of IDP and V-KEMS was able to identify an area where the wider research community could make a significant contribution.

The face-to-face Study Group with Industry model has been run for over fifty years as a very successful way of engaging mathematicians with industry. The aim is to collaborate with industry through problem-focused brain-storming sessions over a period of several days. With the start of the first lockdown in March 2020, it became evident that not only would it be necessary to run all study groups in the near future in a virtual manner, but that the idea of a VSG offered a great opportunity to expand and develop the study group concept, to bring together as wide a group as possible to help generate solutions to a variety of challenges brought about both by the pandemic and in other areas such as climate change and post pandemic economic recovery. Despite the fact that the virtual format is not usually optimal for collaborative mathematics, it helped make study groups accessible to a wider range of people (for example, those who might have caring responsibilities or have difficulties travelling). It has also allowed people (particularly early career researchers) who may be unsure about participating, to join for a short while, try it out and hopefully enjoy it enough to stay and then join future VSGs.

3.4 The Value of Evidence Synthesis

At the beginning of the pandemic there was an explosion in COVID-19-related scientific articles with over 125,000 shared within the first 10 months (Fraser et al., 2021), and more than 30,000 of these hosted-on preprint servers. A key role of scientists working on the COVID-19 response within SAGE and other advisory bodies was to consolidate the latest research and evidence, and present it clearly to decision makers in a timely manner. This involved communicating the balance of evidence and representing uncertainties appropriately. Therefore, one of the most significant challenges for any scientist that was part of the COVID-19 response was the sheer volume and speed at which research was emerging. Furthermore, since much of this research was from preprint servers, careful

scrutiny of the emerging evidence was required due to the lack of peer-review (Majumder and Mandl, 2020).

RAMP's RRG (as described in section 2.2) provided an accelerated review of research outputs. These outputs were nominated for review by those working within government advice channels, RAMP Task Team leaders, and via the RAMP Forums. The RAMP Forums were an online community platform that allowed members to share interesting preprints, comment on them and rate them for policy relevance and scientific rigour. They provided an important structure to support the input of the significant number of researchers who offered their assistance during the initial call for RAMP volunteers and a way to filter through the wider body of emerging research preprints using the community power of RAMP volunteers. The preprints identified as being most significant via the Forums were then passed to RRG. The RRG provided a mechanism for real-time evidence synthesis that was an essential function of reducing the burden of assessing the quality and relevance of research not yet peer-reviewed that would otherwise have fallen on SPI-M and SAGE.

Conclusions

In our increasingly data driven world, it is likely that mathematical modelling will be vitally important in providing scientific advice to governments both in pre-pandemic planning and in the next pandemic emergency. The experience of COVID-19 has shown that there is an immense amount of goodwill in the mathematical modelling and wider mathematical sciences communities to support and advance the mathematical modelling of pandemics in real-time during an emergency. However, it has also highlighted the huge challenge in turning this goodwill into a coherent and effective force. Doing so requires coordination, which, in turn, relies upon infrastructure and resources to facilitate and support coordination efforts.

The success of the initiatives described here relied heavily on existing collaborations, professional connections and friendships and highlighted the challenge of developing new collaborations during an emergency. To ensure we are better prepared for the next pandemic, it is essential to develop an expandable expertise base that can be quickly mobilised to support modelling efforts. This requires understanding at a national level of the location of different expertise, identification of senior level academics willing to establish and lead task force teams and synergies between research areas within the mathematical sciences. Currently-funded national infrastructure (INI and ICMS) were critical in providing this role within the mathematical sciences during the pandemic, with the skills of support staff crucial to ensure coordination of the research activities. The proposed creation of a National Academy for Mathematical Sciences in the UK (Abrahams et al., 2021) and the formation of modelling consortiums (Abdalla et al., n.d.; “https://maths.org/juniper/,” n.d.) provide further mechanisms for the development of national level research networks and expertise. However, such networks require sustained funding to ensure their use beyond the current pandemic emergency.

The phrase the ‘new normal’ has been greatly overused when trying to predict what the future of many aspects of society will look like in the aftermath of the pandemic. From the

point of view of knowledge exchange with the scientific community, there seem to be many lessons that can be learned from V-KEMS. The Forum has won several accolades, notably the *Praxis Auril Knowledge Exchange Team of the Year (2021)*[1] and the inaugural *IMA Hedy Lamarr Prize for Knowledge Exchange in Mathematics and its Applications*[2] to Rebecca Hoyle for her work within V-KEMS. In the specific case of the mathematical sciences, moves are afoot to incorporate all the lessons learned from V-KEMS to build up something more permanent. A model that relies on volunteers and freely donated academic time is not sustainable in the long run, not least because of the stress caused. The creation of a new national network of connected centres for knowledge exchange in the mathematical sciences through the Newton Gateway at INI[3], as proposed by (Jordan et al., 2021), aims to continue to support the collaboration and open engagement and build on the UK's legacy as the founder of the mathematical sciences' Study Group with Industry.

This paper has focused on three initiatives that were put together at the start of the pandemic in the UK to coordinate the efforts of researchers with expertise in mathematics and modelling keen to support the mathematical modelling work in response to the pandemic. However, there were many other initiatives set up during the pandemic to further support collaboration and coordination among researchers. For example, the JUNIPER consortium was constituted in November 2020 and comprised a group of 16 senior researchers from seven different academic institutions across the UK ("https://maths.org/juniper/," n.d.). The JUNIPER consortium strengthened collaborations and coordinated research between a core of committed and experienced research groups that were generating projections and insights that fed into scientific advice relating to the UK's response to the pandemic. There have also been modelling hubs set up outside the UK, for example in the USA and EU (Reich et al., 2022), in an effort to coordinate modelling projections provided to governments, health agencies and the public, thereby helping to generate a consensus in the modelling community.

At the heart of all the coordination activities described here is collaboration and community among academic researchers and the huge value these have in making significant advances in a very short space of time. As Professor Charlotte Deane said in her talk at the *AI and data science in the age of COVID-19* organised by the Alan Turing Institute in Nov 2020 'we all have our own favourite subjects,….,that can make us not great at answering the big questions'[4], therefore the academic community need to work together to address these challenges. The COVID-19 pandemic has raised some of the biggest questions we have had to face in a generation, all of which have had profound consequences on societies across the world. Collaboration between academics from across various scientific backgrounds was key to addressing these questions and highlighted the enormous benefit of supporting the development of partnerships between those with different expertise. But doing so requires a

[1] For more information about the award please see https://www.praxisauril.org.uk/news-policy/blogs/virtual-forum-ke-mathematical-sciences-ke-award-winners
[2] For more information please see https://ima.org.uk/17332/professor-rebecca-hoyle-wins-inaugural-ima-hedy-lamarr-prize/
[3] For more information on the funding supporting this initiative please see this news article https://www.newton.ac.uk/news/ini-news/ini-research-funding-to-double-with-transformative-10m-government-grant/ .
[4] The recording of the talk is here https://www.youtube.com/watch?v=MSVraJX7KRg&list=PLuD_SqLtxSdW7X0ge3NNtoTqkuMfUN82q&index=5&t=366s .

huge amount of coordination to ensure that such collaborative efforts truly enhance the UK's capacity to predict and support decision making around future pandemics. To be successful, this coordination requires investment in resource and infrastructure to be successful.

A key challenge for the epidemic modelling community in the immediate future will be how to continue engagement and capitalise on this interest in the field sparked by the COVID-19 pandemic. The coordination of collaborative activities is pivotal to enabling significant advances in the field and ensuring we are ready with an expandable base of expertise, so that when the next pandemic arrives the mathematical modelling community will be ready.

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