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Getting the most out of maths: How to coordinate mathematical modelling research to support a pandemic, lessons learnt from three initiatives that were part of the COVID-19 response in the UK

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ABSTRACT

In March 2020 mathematics became a key part of the scientific advice to the UK government on the pandemic response to COVID-19. 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 epidemiological 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 epidemiological modelling needed to be coordinated to provide much-needed support, and to limit the burden on epidemiological 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 sciences research community 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. This manuscript was submitted as part of a theme issue on "Modelling COVID-19 and Preparedness for Future Pandemics".

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[1] https://maths.org/juniper/.

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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.[2]

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). Just over 20 academics attended SPI-M meetings (as of Jan 2020). These academics had expertise in modelling the spread of influenza within human populations, representing a small subset of the broader epidemiological modelling research community in the UK. These experts do not receive personal financial renumeration for their role on SPI-M and take on such a role in addition to their academic responsibilities. In times outside of a pandemic emergency SPI-M advise the UK government Department for Health and Social Care (DSHC) on dealing with a pandemic influenza outbreak (Dibben, 2018) and would typically meet a few times a year. SPI-M moved to operational mode (SPI-M-O) at the end of Jan 2020,[3] meaning that it became a formal subgroup of the Scientific Advisory Group for Emergencies (SAGE). SAGE is responsible for providing timely and co-ordinated scientific advice to support UK cross-government decision making during an emergency and participants are chosen depending on the nature of the emergency (see Fig. 1 showing scientific advisory process in UK during the pandemic). Through February and March 2020, several specific 'asks' were being made by the UK government to the experts on SPI-M-O on a weekly (and often more frequent) basis. The size of SPI-M-O was insufficient to deal with this level of activity. Furthermore, members had 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-O 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, researchers within the mathematical sciences as well as mathematical modellers from other academic disciplines 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 epidemiological modellers working directly to provide scientific advice to the UK government, 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 epidemiological 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 epidemiological 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 epidemiological 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 (2020) 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 epidemiological modelling 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 (V-KEMS, IDP research programme and RAMP) 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 UK government. Fig. 2 shows a timeline of when these initiatives began in relation to the pandemic response in the UK. 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.

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. We focus on activities that took place between March 2020 and Dec 2020. During this period the initiatives described here did not receive any direct funding and were leveraging or redeploying existing resources. While two of the initiatives (RAMP and V-KEMS) did receive some additional funding to continue activities specifically related to COVID-19 beyond Dec 2020 we do not discuss those activities here. 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. Referring to specific research communities is challenging as many researchers, particularly those who work across disciplines, may have different interpretations of the areas covered by a given community. In Table 1 we define the terminology we use in this paper to identify the different research communities, noting that these communities are not distinct and there is significant overlap between them. We make the distinction between mathematical sciences and mathematical modelling, as some researchers or practitioners who develop mathematical models have an academic background in a discipline outside the traditional mathematical sciences remit (e.g. geography, immunology) and so may identify as a mathematical modeller but not as part of the mathematical sciences community. A summary of the key activities run by the different initiatives, along with a description of each activity and number of participants is provided in Table 2.

2.1. Virtual forum for knowledge exchange in the mathematical sciences (V-KEMS)

In March 2020, the International Centre for Mathematical Sciences

[2] Powerpoints of all presentations made to the public at UK government briefings are available here https://www.gov.uk/government/collections/slides-and-datasets-to-accompany-coronavirus-press-conferences.

[3] Minuted in the SAGE meeting from 28th June available here https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/https://doi.org/1058445/S0370_Second_SAGE_meeting_on_Wuhan_Coronavirus_.pdf.

(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 epidemiological modelling 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 researchers in fields less commonly associated with the pandemic response such as operational researchers and pure mathematics. Examples included tackling issues proposed by a network of stakeholders regarding the consequences of the pandemic, such as food supply and logistics and ways in which to safely reopen higher education and workplaces following the first national stay at home measures in the UK. In addition, V-KEMS has provided support to existing initiatives such as discussion forums 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.

V-KEMS' signature activity has been the development and delivery of VSGs. These were built upon the framework of the face-to-face Study Group with Industry model which 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. A number of VSGs 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 (Abrahams, 2020). Other VSGs helped to model and propose potential solutions to pre-pandemic problems exacerbated by the pandemic. For example, one explored how mathematical approaches 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 (Butchers et al., 2020). Table 2 provides a summary of the number of events that took place up until Dec 2020 and Appendix A provides a list of the topics the VSGs covered.

Over 350 attendees have participated in the VSGs between April and Dec 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

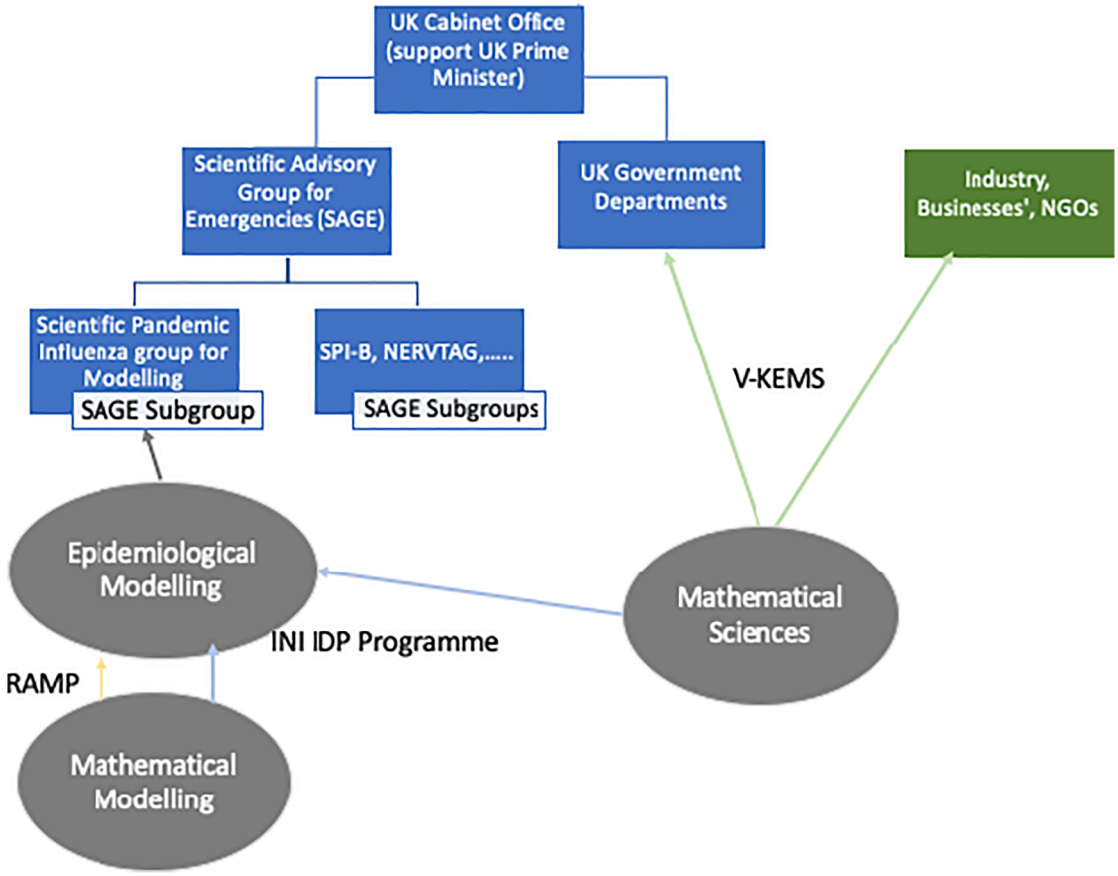

Fig. 1. Organgram showing the scientific advisory process in the UK during the pandemic, the different coordination initiatives described in this paper and the different research communities and stakeholders that these initiatives aimed to coordinate across.

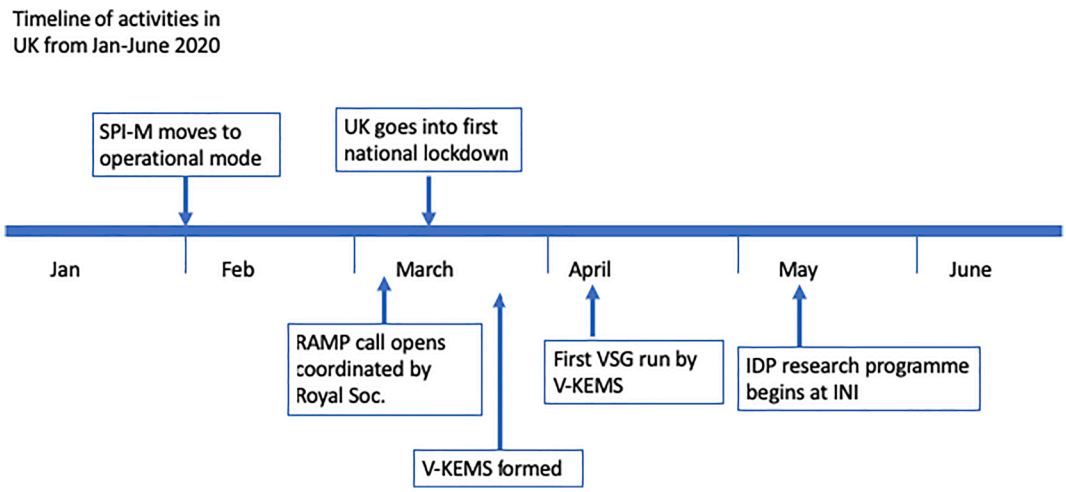

Fig. 2. Timeline showing when the initiatives described here began in relation to the pandemic response in the UK in the first half of 2020.

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 journal articles (Budd et al., 2021; Champneys et al., 2021), working papers (Abrahams, 2020; Enright et al., 2021a) and podcasts.[4] Many V-KEMS activities have also led to longer term mathematical sciences engagement with end-users and to the development of new mathematical ideas. The Forum also won the *Praxis Auril Knowledge Exchange Team of the Year (2021)*[5] and the inaugural *IMA Hedy Lamarr Prize for Knowledge Exchange in Mathematics and its Applications*[6] to Rebecca Hoyle for her work within V-KEMS.

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.[7]

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 epidemiological modelling, indoor transmission, within-host dynamics, structured expert judgement and comorbidities. The volunteers in these areas then connected with the epidemiological 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 h, 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.

2.3. Infectious dynamics of pandemic research programme

On 5th May 2020, the Infectious Dynamics of Pandemics (IDP)

[4] See the V-KEMS website for a full list https://www.vkemsuk.org/publications.

[5] For more information about the award please see https://www.praxisauril.org.uk/news-policy/blogs/virtual-forum-ke-mathematical-sciences-ke-award-winners.

[6] For more information please see https://ima.org.uk/17332/professor-rebecca-hoyle-wins-inaugural-ima-hedy-lamarr-prize/.

[7] See RAMP reports available here https://epcced.github.io/ramp/previous-updates.html#03_April_2020.

Table 1
Table providing definitions of the terminology used to identify different research communities which are used throughout this paper.

Academic Research Community	Definition
Mathematical sciences	Those whose area of study falls within either mathematics or those areas primarily mathematical in nature but may not be considered universally as subfield of mathematics (e.g. statistics or theoretical physics)
Mathematical modelling	Those who try to understand real world problems using mathematical language and concepts.
Epidemiological modelling	Those who develop mathematical or statistical models to understand and/or project the dynamics of infectious disease outbreaks and the impact of interventions within human, animal or plant populations.

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 150 researchers were invited to be participants on the IDP programme, from all career stages, in the UK and internationally (Abrahams et al., 2020). While INI programmes often have this number of participants in total over a 6 month period, IDP was unusual in that there were over 150 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 a 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. See Table 2 for a summary of activities and average number of participants and Appendix B for a list of topics covered in the workshops, seminars and discussions. Talks were recorded and made available on the INI website and a private YouTube channel to enable participation in the programme when most convenient, especially in light of the fact that many were juggling other responsibilities 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 (Blakely, 2020).

In keeping with its aims (responsive, connecting to the wider mathematical sciences 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 topics included modelling for an exit strategy from lockdown,[8] contact tracing and lessons from other diseases,[9] COVID-19 and higher education and, finally, R- how to estimate it and what does it mean.[10] The outcomes of these workshops and discussion sessions were both recommendations and reports sent to government advisory groups[11] (Baggaley et al., 2020; Enright et al., 2021b) as well as peer-reviewed academic papers (Thompson et al., 2021; Vegvari et al., 2021).

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 epidemiological modelling community. These sessions provided academics new to the field the opportunity to discuss the current state of the art in

[8] Recordings of talks are available on INI website here: https://www.newton.ac.uk/event/idpw01/.

[9] Recordings of talks are available on INI website here: https://www.newton.ac.uk/seminar/29157/.

[10] Recordings of talks are available on INI website here: https://www.newton.ac.uk/event/idpw03/.

[11] Links to SAGE minutes where this work presented: https://www.gov.uk/government/publications/isaac-newton-institute-contact-tracing-9-june-2020. https://www.gov.uk/government/publications/isaac-newton-institute-covid-19-and-universities-13-january-2021.

Table 2
Table summarising the key activities of the initiatives described here, including description of the events, number run and approximate participants numbers per event.

Initiative	Activity	Brief Description	Number run	Participant numbers
INI Infectious Dynamics of Pandemics research Programme (IDP)	Seminar	Scheduled talks on a given topic, often presenting work in progress (not public)	23	30-100
	Workshop	Series of talks over several days on a particular theme Talks live-streamed to a public audience	6	100-145
	Discussion Groups	Informal discussion of a specific topic	10 groups (weekly meetings Sept-Dec)	10-30
V-KEMs	Virtual study groups (VSGs)	Collaborate with industry ('problem holders') through problem-focused brain-storming sessions over several days. (Built on the Study Groups with Industry format).	7	~3 problem holders ~65 participants
RAMP	Rapid review group	Reviews on preprints and reports sent to members of scientific advisory groups such as SPI-M and SAGE.	100	~550 members on the forum

epidemiological 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.).

3. Lessons learnt

3.1. Leveraging existing 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 epidemiological modelling 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 epidemiological 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.[12] This led to a set of recommendations (Baggaley et al., 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.[13]

However, a key challenge in leveraging extant networks was trying to incorporate new research areas into activities. There is the danger that inclusion within activities relies upon 'who you know', rather than 'what you know'. Furthermore, this may exacerbate biases and fail to incorporate diversity within activities. To try to minimise these downsides, the initiatives described here relied heavily on the expertise of the knowledge exchange and programme managers within ICMS, INI and the Royal Society. These individuals provided a critical role as a bridge between distinct networks. Their unique overview of the different research networks, and connections to these groups, was critical in quickly identifying relevant areas. For example, V-KEMS relied on the networks with industry through the Newton Gateway, KTN and the knowledge exchange team at ICMS to identify key problems within industry and government. Furthermore, as non-academic roles their primary focus was on the success of the coordination activities rather than raising the profile of their own research interests. A key lesson for the future is that while investing in networks both within the epidemiological modelling community and with other research areas is critical for future pandemics, these networks need to be supported by staff who will ensure coordination of new ideas and diversity.

One final reflection is that while the IDP programme relied heavily on the existing collaborations of researchers that had developed in previous programmes, these networks are typically informal. By this we mean that academics are associated with a particular programme they were a participant on (in terms of data records within INI) and any

[12] Talks from this workshop are available here https://www.newton.ac.uk/seminar/29157/.

[13] See minutes from SAGE meeting on 9th June 2020 https://www.gov.uk/government/publications/isaac-newton-institute-contact-tracing-9-june-2020.

networks that continue post INI programmes are essentially dependent upon individual academics to continue interactions and collaborations. There is no formal support to continue research networks that form at activities such as INI programmes, such as a central coordinator or funding for regular meetings. A big challenge that this raised when the pandemic hit was there was no central coordinator for the epidemiological modelling research network from previous INI programmes and instead it was essentially just individual academics reaching out to other individual academics. A key lesson is that long term support and coordination of research networks that form at events such as INI research programmes or knowledge exchange events is critical for continued and long-lasting impact.

3.2. The pros and cons of the virtual research environment

A characteristic unique to all these events is that, due to the social movement restrictions in place within the UK from March to Dec 2020, all the activities took place virtually. While many have now become accustomed to Zoom meetings and using Teams, this was not the case back in March 2020. 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 also 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. Table 3 contains a summary of the different technologies that were used and or tested at different events with the pros, cons and types of events they were used for.

One of the greatest challenges of the virtual research environment was in trying to develop new collaborations. 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.

Despite the fact that the virtual format is not optimal for collaborative mathematics, it helped make activities 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 events. 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 in the virtual environment. This was where activities such as VSGs were very successful.

While the experiences of the pandemic showed it is possible to run events virtually, it is important to remember the value of in-person meetings in the development of strong academic collaborations. That being said, virtual activities provide a way to significantly improve accessibility and therefore diversity of participants. A lesson for future activities is how we can combine the value of in-person meetings with the benefits of increased diversity from virtual events within a hybrid format going forwards.

3.3. Coordination is key to increase impact

One of the successes of the initiatives described here was the way they coordinated smaller contributions of work from many researchers to increase the overall impact. An example of this was the coordination of work around the topic of COVID-19 and higher education. 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 mathematical sciences 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, 2021b). 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 success of the example given here relied heavily on goodwill of academics to coordinate across multiple teams, willingness of academics to share preliminary unpublished results with each other and the generosity of institutions such as INI to divert resources to support such coordination activities. While coordination across different research groups can provide outputs that are more than the sum of the individual parts, we need to create a sustainable model to ensure such coordination activities are successful long term. This requires valuing and rewarding the expertise of academics who are able and willing to coordinate across academic groups, incentivising academics to share unpublished preliminary work without fear that it will have a negative implication on their publication record (particularly an issue for early career researchers) and provide access to support staff to ensure tangible outcomes from such coordination activities. In particular, the writing of reports from such coordination activities predominantly depended on academics. However, such academics do not necessarily have the expertise, or the time and incentive, to write reports which are accessible to policy makers and are likely to have significant impact within policy. In particular, the lack of staff at INI and ICMS with experience in the area of policy, and in particular in writing reports and documents for government departments, impacted the tangible and direct impacts on policy that the initiatives described here had. A key lesson is that there is great value in coordinating across smaller research groups, but incentivising such activities for researchers as well as supporting staff with expertise in report writing is critical to maximise the impact of such activities.

Here we have shown an example of the value in coordinating outputs of a group of researchers to increase impact, but coordination of research across many different academic institutions is difficult. In particular, a key challenge for the activities such as V-KEMS and IDP was

Table 3
Table summarising the different technologies used for the virtual activities, the advantages and disadvantages of each technology platform and the ways in which the technologies were used to run which events.

Technologies	Strengths	Weaknesses	Activities worked well for
Zoom Meeting	• Easy to record meetings • Straightforward to use • Breakout rooms support smaller discussions	• Easy for participants to 'accidentally ' unmute themselves. • Chat not automatically saved	• Discussion sessions • Study groups • Seminars • Informal networking activities (e.g. virtual coffee breaks)
Zoom Webinar	• Easy to record and live-stream	• Difficult for participants to verbally ask questions • Not good for discussions • Questions not automatically saved	• Plenary talks • Workshop talks
Slack	• Good for short discussion • Supports asynchronous working. • Free • Easy to use	• Needs people to engage with it (e.g. check it regularly or set up notifications)	• Ongoing discussions between events
Sococo	• Recreates 'virtual' office environment • Recreates ability to 'knock' on doors and chat in communal spaces	• Needs people to engage with it (e.g. check it regularly or set up notifications) • Expensive	• Ongoing discussions between events
HackMD	• Free • Allows multiple authors in different locations to edit a document simultaneously	• Takes time initially to become familiar with the environment	• Collaborative writing in real-time
Slido	• Good way for questions to be moderated, stored and answered later • Participants can rate question • Questions can be asked anonymously which is good for participants how may feel intimidated to ask questions • Can run polls	• Separate to the meeting/webinar format • Many participants found the need for an additional piece of software confusing and so didn't engage with it	• Q&A sessions during/after talks
Mural Boards	• Virtual whiteboard which allows multiple participants to edit simultaneously • Very good for brainstorming and running facilitated discussions virtually	• While there are free options, to get the most beneficial features need to pay	• Brainstorming sessions • Virtual facilitated discussions

that they were building upon a model for running events (namely study groups with industry, workshops and seminars) that were not explicitly designed towards a set of outputs for policy makers. This meant that they lacked the structures and expertise within the staff to join up the various research outputs presented at workshops and seminars into useful and meaningful advice for government. Indeed there was a clear lack of a single body to coordinate across the mathematical sciences and interface with other learned societies and which had a very clear understanding of the way epidemiological modelling was used within government. INI and ICMS tried to fill this void, but as we have mentioned they are not set up to coordinate research outputs across the mathematical sciences and as such lacked both the structures and expertise in the staff.

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 pre-print 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 pre-prints, 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.

As the pandemic progressed and the volume of new preprints subsided, the activity on the RAMP forums and reviews conducted by the RRG reduced. The RRG has now ended, due to a lack of need, and the RAMP forums have been shut down and archived by the Royal Society due to lack of engagement. However, they provided a critical function during the initial phases of the pandemic as researchers across the world were trying to share and learn as much as possible about this novel virus. It has been argued that a key success of this pandemic was the pre-printing of academic research, enabling high quality cutting-edge work to be shared very quickly with the wider research community and those advising government.[14] The experiences from the RRG activities provide a model for how to maximise the benefits of sharing large volumes of research quickly which may not have undergone the scrutiny of the peer review process.

4. 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

[14] See a comments from Professor Steven Riley at a panel discussion session at the Royal Society on a modelling the pandemic event held on 13th June 2022. Recording is available here (Professor Steven Riley's comments are 5 h 50 min into the recording) https://royalsociety.org/science-events-and-lectures/2022/06/ramp/.

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.

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. However, the INI and ICMS are primarily set up to deliver research activities, not to coordinate research across different academic groups and critically they lack expertise in the interface between the mathematical sciences and policy. As such, there are few examples from the initiatives described here that had tangible impacts on the policy decisions made in the UK cabinet office. The proposed creation of a National Academy for Mathematical Sciences in the UK (Abrahams et al., 2021) provides a mechanism for the development of national level coordination of mathematical sciences research and expertise to successfully interface with policy makers. Such a new academy along with the other learned societies such as the Royal Society are critical to address point 1 in the 'Principles for coordinating activities in future pandemics' given in Fig. 3.

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. Creation of such national level networks is critical to address point 2 in the 'Principles for coordinating activities in future pandemics' given in Fig. 3. An example of this in the mathematical sciences is the creation of a new national hub for knowledge exchange in the mathematical sciences through the INI,[15] as proposed by Jordan et al. (2021). Such a hub 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. The formation of modelling consortiums (Abdalla et al., 2020; 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 and preparedness for future pandemics. Such sustained funding is rare in academic research with most funding available short term. Therefore, to support long term funding of infrastructure we need to think about how funding models could and should change to support this.

The Rapid Review Group provided a really critical role in quickly synthesisng the latest research related to COVID-19 from preprints and reports for scientific advisors to the government. It provides a model for future pandemics to ensure the latest research is incorporated into scientific advice to government whilst guaranteeing rigorous scrutiny of methods and results which would traditionally happen at the peer review stage in academic publishing. To ensure such a model can be quickly enacted in future pandemics (principle 3 in Fig. 3), a potential structure going forwards would be to have a rolling group of volunteer experts, including an academic lead, who could be called upon in future pandemic emergencies. A challenge though is who would coordinate such a network of volunteers between pandemics. This goes back to principles 1 & 2 in Fig. 3 on the need to longer term support for networks and the importance of centres for coordination.

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',[16] 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 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.

A key challenge for the epidemiological 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 prepared with an expandable base of expertise, so that when the next pandemic arrives the mathematical modelling community will be ready.

CRediT authorship contribution statement

Ciara E. Dangerfield: Conceptualization, Writing – original draft, Writing – review & editing, Project administration. **I. David Abrahams:** Supervision, Funding acquisition, Writing – review & editing. **Chris Budd:** Supervision, Writing – review & editing. **Matt Butchers:** Project administration. **Michael E. Cates:** Supervision, Funding acquisition, Writing – review & editing. **Alan R. Champneys:** Supervision, Writing – review & editing. **Christine S.M. Currie:** Writing – review & editing. **Jessica Enright:** Writing – review & editing. **Julia R. Gog:** Supervision, Writing – review & editing. **Alain Goriely:** Supervision, Writing – review & editing. **T. Déirdre Hollingsworth:** Supervision, Writing – review & editing. **Rebecca B. Hoyle:** Supervision, Writing – review & editing. **INI Professional Services:** Project administration, Software. **Valerie Isham:** Supervision, Writing – review & editing. **Joanna Jordan:** Project administration. **Maha Kaouri:** Writing – review & editing, Project administration. **Kostas Kavoussanakis:** Writing – review & editing, Software. **Jane Leeks:** Writing – original draft, Writing – review & editing, Project administration. **Philip K. Maini:** Supervision, Writing

[15] 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/.

[16] The recording of the talk is here https://www.youtube.com/watch?v=MSVraJX7KRg&list=PLuD_SqLtxSdW7X0ge3NNtoTqkuMfUN82q&index=5&t=366s.

Principles for coordinating activities in future pandemics

1. Coordinate activities through institutions with expertise in combining research outputs from different institutions and direct experience of interfacing with policy makers.
2. Utilise the expertise of knowledge exchange coordinators and programme managers to bridge distinct networks and foster the incorporation of new ideas and approaches into epidemiological modelling.
3. Set up a rapid review process to assess and synthesise emerging evidence to ensure rigorous scrutiny of methodology prior to peer review process.

Fig. 3. Box showing the key principles on coordinating activities for epidemiological modelling in future pandemics.

– review & editing. **Christie Marr:** Supervision, Writing – review & editing. **Clare Merritt:** Writing – original draft, Writing – review & editing, Project administration. **Denis Mollison:** Supervision, Writing – review & editing. **Surajit Ray:** Writing – review & editing. **Robin N. Thompson:** Supervision, Writing – original draft, Writing – review & editing, Project administration. **Alexandra Wakefield:** Writing – original draft, Writing – review & editing, Project administration. **Dawn Wasley:** Project administration.

Declaration of Competing Interest

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: **Ciara E. Dangerfield** is the senior scientific programme manager for the JUNIPER consortium and is on secondment from her position at Isaac Newton Institute for the mathematical sciences as the development and communications coordinator. **I.David Abrahams** is previously director of the Isaac Newton Institute (2016-2021), led the working group to develop a prototype for the National Academy of Mathematical Sciences in the UK, co-led the development of a connected centres for knowledge exchange network for the UK paper, co-investigator on the UKRI funded RAMP continuity network grant and is a forum partner for V-KEMS. **Dawn Wasley** is knowledge exchange coordinator at ICMS and is a forum partner for V-KEMS. **Jane Leeks** is the manager of the Newton Gateway, co-led the development of a connected centres for knowledge exchange network for the UK paper and is a forum partner for V-KEMS. **Clare Merritt** is senior scientific knowledge exchange coordinator at the Newton Gateway and is a forum partner for V-KEMS. **Maha Kaouri** is scientific knowledge exchange coordinate at the Newton Gateway and is a forum partner for V-KEMS. **Christie Marr** is deputy director at the Isaac Newton Institute for the mathematical sciences. **Julia Gog** attended SPI-M, SPI-M-O and SAGE meetings, was co-investigator on the UKRI funded RAMP continuity network grant, is co-principle investigator for the JUNIPER consortium and was an organiser of the Infectious Dynamics of Pandemics research programme at the Isaac Newton Institute. **Deirdre Hollingsworth** attended SPI-M-O meetings, was co-investigator on the UKRI funded RAMP continuity network grant, is a co-investigator for the JUNIPER consortium, leads the Neglected Tropical Diseases modelling consortium and was principle organiser of the Infectious Dynamics of Pandemics Programme at the Isaac Newton Institute. **Chris Budd** is director of knowledge exchange for Bath Institute for Mathematical Innovation, Director of the Centre for Nonlinear Mechanics, Fellow of Gresham College, Professor of Mathematics at the Royal Institution of Great Britain and is a forum partner for V-KEMS. **Matt Butchers** previously part of the Knowledge Transfer Network, currently industrial fellow at Bath Institute for Mathematical Innovation, member of the advisory board for the Newton Gateway, author of the connected centre for knowledge exchange paper and is a forum partner for V-KEMS. **Alan Champneys** is a member of Newton Gateway scientific advisory panel and a forum partner for V-KEMS. **Rebecca Hoyle** is a member of Newton Gateway scientific advisory panel and a forum partner for V-KEMS. **Joanna Jordan** is a freelance mathematical sciences knowledge exchange professional, member of the advisory board for the Newton Gateway, is author of the connected centre for knowledge exchange paper and is a forum partner for V-KEMS. **Michael E Cates** was principle investigator on the UKRI funded RAMP continuity network grant. **Valerie Isham** was one of the organisers of the Infectious Dynamics of Pandemics programme at the Isaac Newton Institute and was previously chair of the scientific steering committee at the Isaac Newton Institute for the mathematical sciences. **INI Professional Services** are predominantly supported through an EPSRC grant no. EP/R014604/1. **Christine Currie** was part of the working group to develop a prototype for the National Academy of Mathematical Sciences in the UK and is a member of Newton Gateway scientific advisory panel. **Alain Goriely** is Director of the Oxford Centre for Industrial Applied Mathematics, Director of the International Brain and Mechanics Trauma Lab, Fellow of SIAM and the IMA, and co-investigator on the UKRI funded RAMP continuity network grant. **Kostas Kavoussanakis** is group manager at EPCC at the University of Edinburgh and co-investigator on the UKRI funded RAMP continuity network grant. **Philip K Maini** was co-investigator on the UKRI funded RAMP continuity network grant. **Denis Mollison** was an organiser of the Infectious Dynamics of Pandemics Programme at INI. **Surajit Ray** is a member of Newton Gateway scientific advisory panel. **Alex Wakefield** is senior policy advisor and programme manager at the Royal Society. **Robin Thompson** attended SPI-M-O meetings and is a member of the JUNIPER consortium. **Jessica Enright** is a member of the JUNIPER consortium.

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Appendix A

List of VSGs run between April and Dec 2020 along with a brief decription of the events.

Modelling of Heterogeneous Systems

Mathematical Modelling and COVID-19: How can modelling inform a response to the current COVID-19 resurgence?

- This workshop brought together people working on modelling the COVID-19 epidemic in the UK to discuss how modelling has and continues to inform policy decision making around this epidemic. It showcased ongoing modelling efforts to evaluate different non-pharmaceutical interventions as well as potential vaccination strategies from the leading modelling groups in the UK, drawing on knowledge from published and in the process of publication work.

Agrifood Data Study Group: Evaluating the UK's resilience to supply chain shocks

- The Covid-19 pandemic has had many negative effects on UK society and the economy. As the UK is not self-sufficient in food production (for example only 16% of fruit and 52% vegetables and salad are grown in the UK), disruption to the logistics infrastructure could have serious knock-on effects for the UK. The often-complex network and interaction of growers, manufacturers, retailers and freight organisations mean that the current crisis is putting a strain on each of these sectors and the infrastructure which support it.
- The mathematical sciences have a role in providing descriptions of resource flows, and tools which can assess vulnerabilities and model possible mitigation strategies.

Feeding Vulnerable People

- This study group looked at how the mathematical sciences can provide support in a) forecasting demand for surplus food products over the coming months and b) incentivising relationships with producers to ensure FareShare is well supported by the food supply chain.

Unlocking Higher Education Spaces

- This three day virtual study group aimed to try to help unlock higher education in the UK following the lockdown. The challenge of opening universities back to closer to normal operation can be seen as a complex, multi-level problem where challenges exist on a building level, a campus level, and a community level.

Guiding Principles for Unlocking the Workforce - What Can Mathematics Tell Us?

- During this 2 day study group mathematicians considered "principles" for how to modify the operation of an individual workplace in order to reduce viral transmission.
- The meeting brought together online a group of over fifty participants, all normally based in the UK. Most were academic mathematical scientists, from a range of specialities. Academics from data science, economics, epidemiology, public health, and behavioural science also took part.

Industrial Maths Virtual Study Group Pilot

- 2 industrial challenges were presented by Zenotech and Scott Bader and over 4 days, study group participants worked on potential solutions.

Appendix B

List of topics covered in seminars run during the INI Infectious Dynamics of Pandemics programme

- Challenges for spatial epidemic models
- Expert judgment
- Contact tracing
- R – how to estimate and what does it mean
- Heterogeneity in R
- Uncertainty quantification
- Within-host modelling
- Urban Analytics
- Advanced UQ
- COVID-19 and high education
- Model inference
- Probability of extinction and interventions
- Reopening of schools
- Data requirements

References

Abdalla, Y., Auty, H., Boden, L., Brett, A., Chen, M., Dundas, R., Marion, G., Matthews, L., Mckendrick, I., Mellor, D., Reeve, R., 2020. Scottish COVID-19 Response Consortium Stakeholder Report.

Abrahams, D., Brown, K., Currie, C., Hoyles, C., Leslie, D., 2021. A National Academy for Mathematical Sciences A Green Paper Foreword 4 Executive summary 6.

Abrahams, D., Marr, C., Aspel, D., 2020. INI Annual Report2019-2020.

Baggaley, R., Ashby, B., Chappell, L., Davis, E., Dye, C., Eggo, R., Fearon, E., Fyles, M., Hampson, K., Menon-Johansson, A., Meyrick, J., Mollison, D., Nicholls, J., Pareek, M., Pellis, L., Scalia Tomba, G., Trotter, C., Turner, K., Webb, C., Yardley, L., Hollingsworth, T.D., Gog, J., 2020. Recommendations for Augmenting Contact Tracing in the UK: Learning from Other Diseases.

Blakely, R., 2020. Models behind coronavirus plans mostly 'educated guesses.'.

Budd, C., Calvert, K., Johnson, S., Tickle, S.O., 2021. Assessing risk in the retail environment during the COVID-19 pandemic. https://doi.org/10.1098/rsos.210344.

Butchers, M., Anjos, M., Brintrup, A., Champneys, A., Currie, C., Coniglio, S., Demirel, G., Eckley, I., Gagarin, A., Quigley, J., Walls, L., McCarthy, B., 2020. UK Mathematical Sciences Expertise for Agrifood Supply Chain & Logistics.

Champneys, A., Wey, A., Dyson, R.J., Alwan, N.A., Barker, M., 2021. The benefits of peer transparency in safe workplace operation post pandemic lockdown. https://doi.org/10.1098/rsif.2020.0617.

Abrahams, I.D., 2020. Mathematical Principles for Unlocking the Workforce-Working Paper.

Dibben, C., 2018. SPI-M Modelling Summary Prepared by the Scientific Pandemic Influenza Group on Modelling.

Enright, J., Erhun, F., Hoyle, R., Lio, P., Penn, M., Pettersson, W., Zhou, Y., Holliman, N., Jiang, H., Lombardo, S., Rudd, J., Schewe, L., Sharkey, K., Sommacal, M., Stickels, C., Weir McCall, J., Champneys, A., Currie, C., Heib, A., Morgan, L., 2021. V-KEMS Study Group Report Modelling Solutions to the Impact of COVID-on Cardiovascular Waiting Lists.

Enright, J., Hill, E.M., Gog, J.R., Tildesley, M.J., Stage, H.B., Bolton, K.J., Nixon, E.J., Fairbanks, E.L., Tang, M.L., Brooks-Pollock, E., Dyson, L., Budd, C.J., Hoyle, R.B., Schewe, L., 2022. SARS-CoV-2 infection in UK university students: lessons from September-December 2020 and modelling insights for future student return. https://doi.org/10.1098/rsos.210310.

Enright, Jessica, Hill, E.M., Stage, H.B., Bolton, K.J., Nixon, E.J., Fairbanks, E.J., Tang, M.L., Brooks-Pollock, E., Dyson, L., Budd, C.J., Hoyle, R.B., Schewe, L., Gog, J.R., Tildesley, M.J., 2021. Isaac Newton Institute: COVID-19 and universities, 13 January 2021.

Fraser, N., Brierley, L., Dey, G., Polka, J.K., Pálfy, M., Nanni, F., Coates, J.A., 2021. The evolving role of preprints in the dissemination of COVID-19 research and their impact on the science communication landscape. PLoS Biol. 19 https://doi.org/10.1371/JOURNAL.PBIO.3000959.

Gog, J.R., 2020. How you can help with COVID-19 modelling. Nature Rev. Phys. https://doi.org/10.1038/s42254-020-0175-7.

https://maths.org/juniper/ [WWW Document], n.d.

https://www.newton.ac.uk/event/sna/ [WWW Document], n.d.

https://www.newton.ac.uk/event/unq/ [WWW Document], n.d.

https://www.sciencedirect.com/journal/epidemics/special-issue/10DM7ZPJKM9 [WWW Document], n.d.

https://www.vkemsuk.org [WWW Document], n.d.

Jordan, J., Butchers, M., Abrahams, I.D., 2021. A Knowledge Exchange Connected Centres Network for Mathematical Sciences A Consultation Document.

Majumder, M.S., Mandl, K.D., 2020. Early in the epidemic: impact of preprints on global discourse about COVID-19 transmissibility. Lancet Glob. Health. https://doi.org/10.1016/S2214-109X(20)30113-3.

Reich, N.G., Lessler, J., Funk, S., Viboud, C., Vespignani, A., Tibshirani, R.J., Shea, K., Schienle, M., Runge, M.C., Rosenfeld, R., Ray, E.L., Niehus, R., Johnson, H.C., Johansson, M.A., Hochheiser, H., Gardner, L., Bracher, J., Borchering, R.K., Biggerstaff, M., 2022. Collaborative Hubs: Making the Most of Predictive Epidemic

Modeling. Am. J. Public Health 112, 839–842. https://doi.org/10.2105/ajph.2022.306831.

Thompson, R.N., Hollingsworth, T.D., Isham, V., Arribas-Bel, D., Ashby, B., Britton, T., Challenor, P., Chappell, L.H.K., Clapham, H., Cunniffe, N.J., Dawid, A.P., Donnelly, C.A., Eggo, R.M., Funk, S., Gilbert, N., Glendinning, P., Gog, J.R., Hart, W.S., Heesterbeek, H., House, T., Keeling, M., Kiss, I.Z., Kretzschmar, M.E., Lloyd, A.L., Mcbryde, E.S., Mccaw, J.M., Mckinley, T.J., Miller, J.C., Morris, M., O'neill, P.D., Parag, K. v, Pearson, C.A.B., Pellis, L., Pulliam, J.R.C., Ross, J. v, Scalia Tomba, G., Silverman, B.W., Struchiner, C.J., Tildesley, M.J., Trapman, P., Webb, C.R., Mollison, D., Restif, O., 2021. Evidence synthesis Key questions for modelling COVID-19 exit strategies. https://doi.org/10.1098/rspb.2020.1405.

Vegvari, C., Abbott, S., Ball, F., Brooks-Pollock, E., Challen, R., Collyer, B.S., Dangerfield, C., Gog, J.R., Gostic, K.M., Heffernan, J.M., Hollingsworth, D., Isham, V., Kenah, E., Mollison, D., Panovska-Griffiths, J., Pellis, L., Roberts, M.G., Scalia Tomba, G., Thompson, R.N., Trapman, P., Gog, J., Hollingsworth, D., Pellins, L., Thompson, R., 2021. Commentary on the use of the reproduction number R during the COVID-19 pandemic. Stat. Methods Med. Res. https://doi.org/10.1177/09622802211037079.