“What happened, and who cared?”
Evidencing research impact retrospectively.

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Abstract
Higher Education Institutions in the UK and elsewhere are under increasing pressure to measure the impact of their research, which can include how the research has increased scientific engagement amongst the general public. For various reasons, the need for evidence can arise months, or even years, after a particular research discovery has been made. Furthermore, the right kind of evidence is needed to indicate genuine behavioural change amongst a given target audience, which can be difficult to obtain after time has passed. In this article, we present a number of strategies for retrospective evidencing of research engagement, and illustrate their use on example discoveries from up to five years ago.

Keywords: Research Impact, Public Engagement, Online Data Mining, Behavioural Change, Evidence

Key Messages:
- It is possible to evidence increased public engagement with scientific research months, or even years, after a discovery.
- Systematic online data mining methods can be successfully employed, using freely available computational tools.
- Different types of online data can be used for mutual corroboration in telling a convincing story e.g. social media data, comments from news articles or videos, and Wikipedia views.

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1 Introduction

Scientific research has long been recognised as a potentially valuable contribution of the higher education sector. Recent years, however, have seen increasing scrutiny of how to quantify this value. After all, the financial resources available for science are necessarily finite. Evaluating the relative benefits of different research programmes can help in the allocation of these limited funds. Furthermore, assessing the wider implications of research is a way of systematising a moral obligation that many scientists feel: that they should justify to funders – including the taxpayer – why their research is important.

The wider value of scientific research is usually referred to as \textit{(research) impact}, and different definitions are adopted in different academic contexts. Typically, however, one identifies one or more \textit{target audiences} outside academia, and then defines impact as a \textit{change in behaviour} of the audience(s). This is the approach adopted by the UK Research Excellence Framework (REF) \cite{REF}, and an advantage of this definition is its flexibility. For example, the impact may be commercial or policy-based, where appropriate target audiences may include companies or governmental organisations respectively. In this article, however, we will be concerned with cultural or societal impact, and the target audience we have in mind will be the general public. We may then talk about the \textit{reach} of any impact (how many people the research influenced), and its \textit{significance} (how deeply they were affected). Whilst the former of these can be relatively easy to demonstrate in large numbers (e.g. through audience figures for a media outlet), the latter is notoriously difficult.

For certain types of event (e.g., those falling under a traditional public engagement banner, such as outreach talks or museum exhibitions), one would usually include the evidencing of impact at the project design stage. Examples include the use of before/after questionnaires, or other similar means of gauging opinion, to explicitly demonstrate that impact has occurred. Indeed, this is usually required by funding bodies. For instance, the UK Research Councils have developed criteria for designing and evaluating public engagement activities both individually (see, for instance, the STFC Public Engagement Evaluation Framework \cite{STFC}) and through overarching bodies such as the National Co-ordinating Centre for Public Engagement. However, whilst the significance of impact in such cases can often be well demonstrated, the reach tends to be low.

An opposite case is that of individual research discoveries that are shared widely by the media. Here the reach, as measured by viewing figures or other metrics, can be enormous (the case studies presented herein involve millions of people). However, this does not by itself demonstrate any impact, as the latter requires an explicit demonstration of behavioural change, which can be difficult to achieve \cite{CulturalImpact}. There may be ways around this – such as looking at impact on science journalists themselves rather than the public they broadcast to \cite{ImpactOnJournalists} – but it remains desirable to consider the impact of research on society as a whole. Compounding this problem is the fact that evidence for such impact may need to be collected months, or even years, after a particular discovery has been made, reasons for which include the following:

- Reaction to a given research event may not be immediate, as it may take some time for its importance to be realised.

- It may not be realised \textit{a priori} that a given event will receive widespread attention, and thus mechanisms for recording its impact may not be put in place.

- A given institution may lack resources or frameworks for systematically evidencing research impact as and when it occurs.
• Changing external factors or assessment criteria for research institutions may create a need for evidence-gathering that was absent at the time of the discovery.

The question of how to retrospectively evidence research impact is highly topical, given the growing impact agenda in the UK and elsewhere.

A promising new avenue towards demonstrating research impact among a broad public comes from the fact that we are living in a golden age of data science. The ubiquity of computer resources and the internet make potential sources of evidence both more varied and voluminous than ever before. This already suggests that a number of different online datasets might be useful for demonstrating impact, relating e.g. to social media or news articles. Whilst some tools exist for analysing such data, however, they are not necessarily geared towards evidencing research impact, as ref. [3] has recently highlighted. The main reason for this is simply that specialist academic knowledge of the research in question can be useful in informing the design of suitable data-mining tools.

The aim of this paper is to demonstrate a number of ways that online data mining can be used to evidence the impact of research discoveries, where the latter may be a few years old. Our target audience will be members of the general public, and the types of behavioural change that we will seek to evidence include: (i) widespread discussion of a particular discovery or research event; (ii) increased engagement with a broad research area (e.g. astronomy) following a specific event; (iii) increased understanding of research topics or details. Importantly, we will try to tie these changes to specific research papers or findings, which can be a requirement of some impact assessment exercises.

The structure of our paper is as follows. In section 2 we outline the various online data sources that we will consider, and describe the computational methods we have used to accrue sufficiently large datasets for analysis. In section 3 we will analyse the data we obtain in specific examples of fundamental physics discoveries in the past few years, and present in each case examples of behavioural change. We discuss our results and conclude in section 4.

2 A survey of online data sources and ways to interact with them

The internet provides a large number of avenues for the general public to engage in scientific research. Conversely, this allows academics (or other research stakeholders) multiple entry points for evidencing the societal impact of their results.

While each individual site offers unique ways to interact with its material, a generic set of responses has become widely available, which we summarise in Table 1. These responses require different amounts of time (e.g., “liking” a post is faster than writing a paragraph in response to it) and may be more or less public (e.g., Twitter “likes” are publicly available, but “retweets” are explicitly drawn to the attention of all followers). This might provide a helpful scale of engagement: responses requiring greater time or social commitment (i.e., towards the bottom right corner of Table 1) represent greater engagement.

In this section, we concentrate on a number of specific sources of online data, and briefly describe how they can be used to construct narratives of behavioural change.

4The need to tie impact to specific research papers was a formal requirement in REF2014, but has been relaxed slightly (i.e. to allow reference to a body of work of associated individuals) in REF2021 [1].
### Table 1: Schema of different generic ways to engage with online material on news sites or social media.

We argue that, in general, greater time or social commitment both indicate greater engagement.

#### 2.1 News articles

Whilst television remains the most popular source of news, its use is falling. On the other hand, news consumption via the internet is rising, with 66% of all UK citizens aged 16+ relying on it in 2019. This outstrips similar figures for radio (43%) and newspapers (38%). Furthermore, internet use dominates over television for two (overlapping) demographics, namely young adults (aged 16-24), and certain ethnic minorities. From an impact point of view, internet news has a distinct advantage over traditional TV or print sources: many news websites allow users to post comments on any given story. These comments may be supplemented by additional information, such as a unique name or identifier for the author of each comment, their geographical location, and a date or time stamp for the comment itself. Some news websites allow users to rate comments using likes and / or dislikes. Three of the most popular news websites in the UK are the Mail Online (an offshoot of the Daily Mail newspaper), BBC News and The Guardian (n.b. all of these outlets are free to consume, with no registration required). Each of these three websites allow user comments, although not necessarily on every story. Readership figures and additional comment functionalities are summarised in table 2.

Popular news stories can generate many (hundreds of) thousands of comments, straddling a few years in some cases. It is clearly inefficient to collect comments from large numbers of articles by hand. However, the procedure can be automated using well-established computational techniques. More specifically, we have written computer codes in the Python language, that in turn rely on the publicly available packages Selenium (for automated web browsing) and Beautiful Soup (for parsing of website source code in HTML). These can be used to efficiently strip comments from an arbitrary news article associated with a given outlet, although custom codes are required for each news source. For the present study, we have manually searched for news articles relating to specific research results, although this could also be automated in principle.

There is clearly a large amount of information contained in news comments. For example, numbers of comments on any given article, as well as location information, can be used to estimate the (inter)-national reach of a given discovery. Numbers of positive and negative responses can

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| Social commitment | **Low** | **High** |
|-------------------|----------------|----------------|
| **Time commitment** | **Low** | **One-click reaction** |
| “Liking” material. Reactions may be displayed as a total number and/or used to sort comments. | | One-click recommendation |
| *Examples*: Twitter “likes”, Reddit “up/downvotes”, news site reactions | | Sharing results with friends on a social network, without further comment. |
| **High** | Learning more |
| Following up references from media, either through explicit hyperlinks or by searching for keywords. | | Initiating or contributing to ongoing discussion. |
| *Examples*: Wikipedia page visitor history | | *Examples*: Twitter “quote retweets”, news site “share” buttons |
| | Sharing knowledge |
| | or new tweets, Reddit replies or new posts, independent blog articles |
Table 2: Reach and comment functionality for three main UK news websites. Here the readership figures correspond to the total unique visitors / viewers in November 2019, and are taken from comscore.com. Also ✓ * denotes the fact that the Mail Online timestamp information becomes incomplete for older comments. Furthermore, + and − indicate whether positive or negative responses to comments are possible respectively.

| News outlet     | Readership | Date & Time | Location | Response |
|-----------------|------------|-------------|----------|----------|
| BBC             | 35M        | ✓           | ×        | +/-      |
| Mail Online     | 34M        | ✓ *         | ✓        | +/-      |
| The Guardian    | 24M        | ✓           | ×        | +        |

Figure 1: The number of active Twitter users as a function of time.

evidence which particular aspects of a news articles people are most strongly engaging with, and it may be possible to relate such aspects to specific research papers. Of course, a wealth of qualitative information is contained in the texts of the comments themselves. One may look e.g. for prevalence of keywords in order to ascertain if given topics are being talked about, or evidence of conversation or debate involving two or more commenters.

2.2 Social Media

Social media platforms such as Twitter and Facebook allow users to share scientific information (including news articles), and to comment on its significance or implications. Indeed, roughly half of UK adults now use social media for news [5]. Here, we will focus on the Twitter platform, whose number of active users has risen remarkably in the past decade, remaining relatively stable from 2015 onwards (see figure 1). The Twitter website and app allows users to post short (140 character) “tweets” for consumption by their “followers”, which may or may not include additional media such as images or weblinks. Each tweet carries the name of the tweeter (and their unique Twitter handle), as well as date information. Users may reply to the tweets of others, and also “retweet” them, so that they are shared for their own followers to see. Finally, users can “like” the tweets of others,
such that any given tweet can be characterised by its number of replies, retweets and (positive) reactions.

Tweets may be mined retrospectively in a similar fashion to the news comments of the previous section. Twitter itself provides dedicated packages for Python, which can be used to systematically mine tweet information in real time, or access past tweets. In particular, one may search past tweets for certain phrases or keywords, including “hash-tags” (Twitter’s own special keywords, which are always preceded by the # symbol). Examples of the use of Twitter data are similar to that mentioned for news comments above. However, social media has the advantage that the numbers of people engaging with a given tweet or topic can be much larger: we will see examples involving hundreds of thousands of people in what follows.

2.3 YouTube

YouTube is a global video sharing platform, with over 1.9 billion logged in users per month. Anyone can register to upload videos on the site, and the ubiquity and on-demand nature of its content (70% of which is viewed on mobile phones) means that it is replacing traditional TV-based science content for many people. Examples of research-based videos considered here include those created by public organisations (e.g. NASA), journalists, and dedicated YouTube science channels. On each YouTube video page, one may easily see the number of views a video has had, and a number of positive and negative reactions (analogous to the likes and dislikes in news articles). Viewers may comment on videos, and the sheer number of viewers involved (sometimes several millions) means that a large amount of comment data can be mined, using similar methods to those described above. Each comment has a number of “votes”, which plays a similar role to the number of positive reactions for news comments. One may also obtain date information for each comment, although this becomes less precise for older comments.

2.4 Wikipedia

Wikipedia is a free online encyclopedia, that anyone can edit. It has rapidly become a goto online resource, replacing traditional print encyclopedias, particularly given its dynamic nature that can respond to events and discoveries in real time. It attracts hundreds of millions of monthly visitors, and contains roughly 50M articles, in 302 languages. Web pages exist for specific topics, and are also linked together so that one can easily view pages which are closely related to a given article. Data on Wikipedia usage, including page views in different languages and / or as a function of time, can be easily exported from the publicly available tool PageViews Analysis. Examples of how to use this data include evidencing the reach of public impact associated with a particular discovery, which is particularly straightforward if a dedicated Wikipedia article exists. Another very useful idea is to look at correlations between different articles: one may try to argue that people who engage with a particular discovery or research result are in turn more likely to read more widely about the underlying subject and context of the research. This narrative becomes particularly powerful if combined with data from one of the alternative sources outlined in the previous sections.

2.5 Reddit

Reddit is a news aggregation and discussion website, that proudly calls itself “the front page of the internet”. Users can post texts, web links (e.g. to news articles) or images, which are grouped into
subject-specific forums or *subreddits*. Each post can be voted up or down by website members, so that individual posts may move to the top of a given subreddit, or even appear on the main website itself. Reddit is the 18th most visited website in the world, with 42-49.3% of users originating from the US, and 7.9-8.2% from the UK. There are a number of insights that can be obtained from analysing Reddit data. Firstly, there are quantitative metrics such as the number of posts relating to a given research discovery as a function of time, and the number of upvotes received. Such information can be used alongside similar metrics from analysing Wikipedia and Twitter data, in order to build a consistent narrative of public engagement. One may also look for use of specific images relating to a given research project, and measure the proportion of posts which feature them. Secondly, there are valuable qualitative details that can be gathered from Reddit data. Each subreddit corresponds to a distinct community of people, united by a special interest. The different subreddits that discuss a particular research discovery then provide a cross-section of which societal groups have been enthused. Not only can this be used to classify the impact of a particular discovery, but it can also inform the design of future impact strategies.

In summary, we have described a number of different avenues for collecting online data related to public engagement with scientific research. Each of these in isolation tells an incomplete story, and must be used with care. In particular, one has little or no knowledge of the demographic associated with each online tool. However, by combining information from different sources, one can start to build up a more complete picture of how a given set of research results has entered the public consciousness, and generated discussion and / or debate. Let us now begin to do this, by focusing on specific examples.

3 Examples of specific research projects

3.1 The discovery of Proxima b

A significant focus of astronomical research in recent years has been the search for *exoplanets*, namely planets which orbit stars other than our own Sun. As well as the intrinsic interest in cataloguing the presence of celestial bodies outside our solar system, the study of exoplanets may yet reveal the existence of extra-terrestrial life. Discovery of the latter would lead to a profound reevaluation of our place in the universe, and have far-reaching implications for the philosophy and religious faiths of humans around the globe. In 2016, the *Pale Red Dot* project discovered an exoplanet orbiting our nearest star, Proxima Centauri, which itself forms part of the Alpha Centauri star system [6]. This remains the nearest exoplanet to Earth ever discovered. Furthermore, ongoing studies of its environment suggested that it may harbour conditions for extraterrestrial life. These facts led to considerable media reporting and attention worldwide, including print, broadcast and online media. As discussed above, however, this does not by itself constitute impact of the discovery, given that merely encountering a news article does not necessarily amount to behavioural change of the observer. In order to measure the latter, we have used the computational methods discussed in section 2 to construct a database of over 57.5k tweets relating to “Proxima Centauri”. Our use of this particular search term is motivated by its being the parent star about which the newly discovered Proxima b orbits. Discovery of the star predates the discovery, such that we would expect increased discussion relating to Proxima Centauri to correlate with key dates in the discovery timeline of Proxima b. We have also accrued 4910 news comments (from the Daily Mail, Guardian and BBC websites); 1583 Reddit posts relating to Proxima b from 484 distinct subreddits;
and Wikipedia information using PageViews Analysis. This allows us to provide evidence for an increased public engagement in astronomy topics relating to exoplanets, Proxima Centauri and the likelihood of extraterrestrial life.

In figure 2(a), we show the number of retweets which contain the term “Proxima Centauri”. We choose retweets rather than tweets, as these indicate a more active engagement of twitter users, who have thus explicitly chosen to rebroadcast a particular piece of information. Likewise, in figure 2(b), we show the number of replies to tweets featuring the same search term. Both plots start with a gentle rise in discussion, which comparison with figure 1 reveals is not due to increased public engagement with astronomy, but rather the increase in the number of global Twitter users. Nevertheless, the most dramatic feature in both figures 2(a) and (b) is a highly pronounced spike in activity coinciding with the discovery year (2016) of Proxima B. The number of global retweets for the selected search term was over 23 times higher than the four-year average pre-discovery, and the annual average post-discovery is almost 8 times the average pre-discovery. This is far in excess of the rise in the number of Twitter users in this period. Furthermore, the trend in engagement post-discovery is upward, indicative of a sustained impact, as Proxima b enters wider popular culture, with increased media references.

A similar story is told by the Wikipedia data: figure 3 shows the number of views of the Wikipedia pages for Proxima Centauri (in 73 different languages) as a function of time. A significant spike is seen around discovery, and a sustained increase in activity occurs afterwards. To quantify this, we may avoid the spike by calculating the average number of views after 1st October 2016, and before 1st August 2016. We then find an average increase in engagement of 30%, amounting to 20k extra views per month. On Reddit, there were over 350 posts on the discovery date itself, and there has been a sustained activity since, with around 4.7 posts per week on average.

The quantitative results above show increased engagement of the public with astronomy related to the discovery of Proxima b. Further valuable insights on the nature of the impact can be gained by examining qualitative data. First, we may perform a keyword analysis on the collected texts in our database of tweets. Figure 4(a) shows the average number of retweets and replies for tweets containing certain keywords. Depending on which measure is used, above-average activity is strongly associated with the concept of habitability. Our other chosen keywords demonstrating above-average engagement are clearly related to the potential existence of extra-terrestrial life, and we found that
the number of tweets containing the words “habitable”, “water”, “alien” or “life” strongly increased after the 2016 discovery, an increase that continued thereafter. Similar results arise from analysing our collected news comments: figure 5 shows the average number of reactions for news comments containing various keywords. As well as corroborating the interest in alien life, above-average engagement is also observed for comments discussing the implications of the discovery for religion, as well as the possibility of interstellar travel to the exoplanet (the latter was well-publicised after a press conference for the Breakthrough Foundation, who initiated a project to send small spacecraft to Proxima b). This consistency of popular keywords across different media platforms significantly supports the hypothesis that public interest in the Proxima b discovery focuses on its implications for the existence of life outside our solar system.

The Twitter data already provides evidence that more people are finding out about Proxima Centauri as a result of the Proxima b discovery. It is also possible to show this also using the Wikipedia data. In particular, one may look at correlations between viewing figures for different Wikipedia articles. Proxima Centauri b (to use the full name of the exoplanet) has had its own Wikipedia article since 24th August 2016. One may then plot the viewing figures for related articles on a particular day, vs. the viewing figures for the Proxima b article. We show this in figure 6 for the articles on Proxima Centauri and Exoplanets. There is a clear correlation in each case, suggesting that people who are reading about Proxima b are in turn seeking out more information on the host star, or on Exoplanet research in general. The positive correlation can be quantified in each case by the well-known Pearson correlation coefficient, which is one for complete (positive) correlation, and zero for no correlation. The Pearson coefficients are 0.84 and 0.30 for the Proxima Centauri and Exoplanet articles respectively, with negligible uncertainties. Correlation does not imply causation in general, and there are known statistical problems when comparing time series of

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5Given that the Proxima b article appeared originally only in English, we have chosen to compare correlations with related articles in a single language.

6One may worry that the statistical assumptions underlying the use of the Pearson coefficient - that of a linear relationship, and Gaussian uncertainties for the viewing figures - do not apply here. An alternative is to use the Spearman coefficient, which evaluates to 0.72 and 0.37 for the two cases.
Figure 4: (a) The average number of retweets for tweets containing “Proxima Centauri”, containing certain keywords; (b) Similar but for replies. In each case, the dashed line indicates the average activity for all “Proxima Centauri” tweets.

Figure 5: Average number of reactions for news comments containing certain keywords, where the dashed line denotes the average for all comments in the selected articles.
Figure 6: Viewing figures for Wikipedia articles, plotted against the viewing figures for the article *Proxima Centauri b*, taken on the same day.

data, as we are doing here. However, the fact that the Wikipedia correlation agrees with similar conclusions reached from the social media data, means that one can be confident that a genuine correlation is being observed.

In addition to the keyword analysis above, one may examine which groups of people were particularly influenced by the *Proxima b* discovery. The Reddit communities with the highest proportion of *Proxima b* posts include one focused on creative writing and another dedicated to “exhibiting the awesome potential of humanity”, indicating that *Proxima b* has uniquely captured public imagination beyond typical astronomy-interested audiences.

### 3.2 The Cassini-Huygens mission

As a second example of a research with a significant public engagement component, we use the results of the *Cassini-Huygens probe*. This was a NASA satellite mission, which reached the planet Saturn in 2004. It then spent 13 years orbiting the planet, performing detailed observations of its moons and ring systems, including Enceladus and Titan, which are thought to be potentially habitable by microbial extraterrestrial life. In September 2017, the mission culminated in a spectacular *Grand Finale* phase, in which the probe was destroyed by intentionally crashing into Saturn, in order not to contaminate the nearby moons. During its lifetime, the Cassini-Huygens mission captured over 400k images of Saturn and its environs. These generated new research results in planetary mechanics, but also gained widespread public interest. One picture in particular - dubbed “Cassini’s most iconic image mosaic” by NASA Project Scientist Linda Spilker - featured a high-resolution shot of Saturn, with the Earth as a tiny speck in the background. The striking poignancy of the image was highlighted by news outlets around the world. Likewise, the Grand Finale phase of the mission also received widespread media attention.

Similar to the exoplanet discovery discussed in the previous section, the Cassini mission is able to potentially stimulate public interest in astronomy. It may also have changed the status quo regarding how society at large both visualises and understands Saturn. Proving this retrospectively, however, poses different challenges to the previous example. Despite the fact that iconic images have been produced - whose (re-)use in online media can potentially be traced - there is not necessarily a clear demarcation between “before” and “after” when it comes to discussing Saturn.
In the exoplanet example, Proxima b did not exist before its discovery, and so any discussion of its properties constitutes a shift in public understanding. This is not the case with Saturn, such that different ways of thinking about its impact are needed. Nevertheless, similar techniques may be used to the previous section, in building a coherent narrative for public behavioural change. To this end, we have amassed 223k tweets relating to the search string “Saturn Cassini”, from 2013 onwards; 6080 comments from news articles relating to Cassini on the Daily Mail, Guardian and BBC websites; 12,300 comments from YouTube videos relating to Cassini; over 125k Reddit posts relating to Saturn in over 12k distinct subreddits; and Wikipedia pageview data using PageView Analysis.

Quantitative evidence for a sustained increase in public engagement with the mission is revealed in the Twitter data. In figure 7, we show the number of retweets and replies to tweets relating to “Saturn Cassini”, which demonstrate a clear peak in engagement throughout the Grand Finale year e.g. there were over 287k retweets in 2017, 9.5 times higher than the mean in the preceding three years. There is also a sustained increase thereafter, showing widespread engagement with the mission’s legacy. Our Reddit data also shows a sustained increase in engagement with Saturn-related content, with weekly posts rising from a baseline of around 200 to around 800 after the peak in 2017 (figure 8), with a notable rise thereafter. Wikipedia data confirm this picture. We found, for example, that page views for Wikipedia’s articles on Saturn spiked by approximately a factor of 9 during the Grand Finale orbit. In figure 9, we show the viewing figures for articles on the Cassini-Huygens mission (in 72 different languages). The two large spikes correspond to the start and end of the Grand Finale orbit, which both received major press attention. One expects, in the case of Cassini, that it has set a new paradigm in how we visualise Saturn, in that images have become definitive, even amongst the general public. This can be evidenced by looking at our Reddit data, and in particular the number of image-related posts about Saturn. In a sample of 5645 posts, we found that 18% feature Cassini images, showing that significant numbers of people are choosing Cassini results to illustrate their discussions.

As for the exoplanet discovery discussed above, one may perform a keyword analysis to see which aspects of Cassini science are the drivers of public engagement. Interest in the moons (e.g. Titan) is evident, as are new results on the ring system. The keyword “Earth” gets the most attention, which is tied to the iconic Day the Earth Smiled image mentioned above. Interestingly, engagement
Figure 8: Rise in Reddit activity related to Saturn.

Figure 9: Daily viewing figures for Wikipedia articles on *Cassini-Huygens* in 72 different languages, where the curve has been smoothed with a 30-day rolling average.
Figure 10: (a) The average number of retweets for tweets containing “Saturn Cassini”, containing certain keywords; (b) Similar but for replies. In each case, the dashed line indicates the average activity for all “Saturn Cassini” tweets.

Figure 11: (a) The average number of reactions for comments relating to the Cassini mission, from (a) news articles; (b) YouTube videos. Also shown is the average number of reactions across all comments.

as measured by replies to tweets (perhaps a more active measure of engagement) is significantly higher than average, as compared to retweets. This story is replicated by reaction data taken from news article comments, and from YouTube videos (figure 11). In the latter case, interest can also be seen in Enceladus (another of Saturn’s moons). Comments which explicitly talk about the wonder conveyed by Cassini images (as measured by the word “Amazing”) also lead to increased engagement.

Evidence for the public educating themselves can again be gleaned by looking at correlations of Wikipedia page views. In figure 12 we show the page views for related articles to the Cassini-Huygens article (across all languages), compared with the latter article itself. There is a clear correlation with people reading about Saturn in general, or the ring system: the respective Pearson correlation coefficients are 0.43 and 0.70, with negligible uncertainties. As for our previous research example, the fact that the keyword analysis tells a similar story of engagement means that we can

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7 The respective Spearman correlation coefficients are 0.35 and 0.39, again with negligible uncertainties.
be confident that a genuine correlation is being observed. Further qualitative insights can be gained by looking at which Reddit subforums users are engaging with. We found that the top 20 subreddits for Cassini-related discussions include nine focused on general photography and general interest posts. In 2019-2020 there was an average of five posts a week, even on advanced topics such as the moon Enceladus. Thus, the image-related aspect of the Cassini mission has indeed informed discussions in communities outside of typical science channels. Unsurprisingly, Reddit posts with the most upvotes convey inspiration and wonder; we found multiple posts with more than 10,000 upvotes and / or more than 1,000 comments. Qualitative information from comments can be highly useful. In our database of combined news and YouTube comments, for example, we found evidence of the following:

- *Increased understanding* of space exploration e.g. “$4bn well spent - the knowledge Cassini has provided has broadened our understanding of our Solar System and hopefully paved the way for future manned exploration.” (a news comment with 342 reactions).

- *Specific references to scientists* from particular institutions (n.b. this can be useful for assessment exercises such as the REF).

- *Debate and discussion* about complex scientific topics. In the Cassini case, the YouTube comments show people discussing the nature and structure of Saturn’s rings (e.g. “Saturn has moons between its rings that produce ripples in the rings through gravity...interesting!”); why the Cassini mission flew into Saturn and the proof that it did so; and the nature of the instrumentation on board, and how this influenced the reported images (e.g. “Cassini’s speed is the reason these particular photos are only in greyscale and low resolution on this pass”).

### 4 Conclusion

In this paper, we have examined the problem of how to evidence the impact of well-publicised research discoveries on the general public, years after a given discovery took place. By exploiting the wealth of data available online, we have constructed narratives of increased public engagement
for two example high-profile research projects: (i) the discovery of the exoplanet Proxima b in 2016; (ii) the Cassini-Huygens mission, which culminated in a spectacular Grand Finale in 2017. We have constructed our own computational tools for extracting and analysing Twitter data, Reddit posts, Wikipedia views, and news / YouTube comments. This is greatly advantageous to using pre-existing online metrics or tools, which would need to be tailored to be able to incorporate specialist research knowledge related to the projects at hand.

Whilst each data type by itself may provide relatively weak evidence for behavioural change, the combination of several mutually corroborative elements leads to much stronger conclusions. We found convincing evidence for increased public awareness of astronomy topics; discussion and debate of advanced scientific concepts; and a sustained legacy of engagement with our chosen research results. This suggests that similar methods may prove useful in future, particularly for the kind of fundamental physics discoveries that - whilst highly publicised - can be tricky to describe in terms of the impact narratives required by assessment exercises such as the REF.

Our paper is very much a proof-of-concept study, and there are clearly many avenues for future research. The investigation of research projects which are not quite as high-profile as the ones presented here would be interesting, as would the extension of our datasets to include more types of online data. It would also be possible to do a much more sophisticated analysis of our comment databases. One might think, for example, of applying sentiment analysis, natural language processing (or other machine learning) techniques in order to quantify how the public’s response to scientific content changes over time, or to quantify evidence of rigorous debate. We leave the investigation of these interesting questions to future work, noting that the increasing impact agenda, together with the rapid development of data science, provide ample scope for interdisciplinary collaboration in this area.

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