Meta and consensus forecast of COVID-19 targets

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SUMMARY FINDINGS

As of Feb 28, 2021 there are a reported 29,982,984 cumulative confirmed COVID-19 cases, 524,494 cumulative deaths due to COVID-19 according to the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University, and on Feb 27, 2021 there were 6,100 US previous day adult and pediatric admissions to the hospital because of COVID-19 as reported by the Department of Health and Human Services.

We aim to provide two types of probabilistic forecasts of the U.S. COVID-19 outbreak to support public health officials, infectious disease modeling groups, and the general public. The first forecast is an aggregate of probabilistic predictions from experts in the modeling of infectious disease, and trained and untrained forecasters called a *consensus forecast* (Sec. II and Sec. III). The second forecast is a combination of our consensus forecast and the COVIDhub-ensemble, an ensemble of computational models hosted by the COVID-19 Forecast Hub. This combination of predictions from computational models and from trained, generalist, and expert forecasters is called a *metaforecast* (See Sec. IV).

A consensus of experts in the modeling of infectious disease and trained forecasters from Metaculus predicts, for the week beginning Feb 21st and ending Feb 27th, a decrease in the number of pediatric and adult hospital admissions (median = 47,000; 80% CI = [29,000, 67,000]), decrease in the number of new confirmed cases of COVID-19 (median = 540,000; 80% CI = [300,000, 870,000]), and a decrease in the number of new deaths due to COVID-19 (median = 15,450; 80% CI: [10,650, 20,400]). Generalist forecasters from Good Judgment Open (GJO)—an online forecasting platform open to any interested member of the public—made forecasts in line with forecasts from Metaculus. When asked the same set of questions, forecasters from GJO assigned a probability of 46% to fewer than 45,000 incident hospital admissions, a probability of 64% to fewer than 600,000 incident cases, and a probability of 35% to between 14,000 and 16,000 incident deaths.

To help public health officials better predict the effect of vaccination on the trajectory of the US COVID-19 pandemic, we asked forecasters to predict the cumulative number of people who will have received one or more doses of a COVID-19 vaccine by Feb 28th. The consensus among Metaculus forecasters is that by Feb 28th, 55,420,000 people will have received at least one dose of a vaccine (median = 55,420,000; 80% CI = [48,170,000, 68,180,000]). Forecasters from GJO responded similarly with an implied median of 52,200,000 people receiving one or more vaccine doses.

In the past two months, three SARS-COV-2 variants of concern (B.1.1.7, B.1.351, P.1) have been publicly monitored by the CDC. A consensus forecast assigned the highest probability to the CDC monitoring 4 variants of concern by 2021-03-07, one additional variant than currently reported at US COVID-19 Cases Caused By Variants.

Information about the spread of the B.1.1.7 variant—the variant that was identified in the United Kingdom and found in more than 98% of UK SARS-CoV-2 samples sent for genomic sequencing—in the US has the potential to impact decisions about non-pharmaceutical interventions and changes in the pace of vaccination. A consensus of subject matter experts and trained forecasters from Metaculus predict 42% of US samples sent for genomic sequencing in the first two weeks of Mar. that have an S-gene mutation (a mutation present in all B.1.1.7 samples) will be identified as the B.1.1.7 variant. (median = 42; 80% CI = [15, 80]). Experts and forecasters expect this to increase to 72% between 2021-03-29 and 2021-04-04 (median = 72; 80% CI = [43, 95]).

Metaforecasts—combining the COVID-19 Forecasthub ensemble, Metaculus consensus, and Good Judgment Open consensus—were generated for the number of incident confirmed cases and incident deaths for the week of Feb 21th, 2021 (Fig. 2). The Metaforecast's 80% prediction intervals were larger than the COVIDhub ensemble prediction intervals but smaller than prediction intervals generated from a consensus of experts and trained forecasters. A metaforecast can combine forecasts from computational models and a consensus of human judgment and has a level of uncertainity between that of computational models and a consensus of human judgment.

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I. CONSENSUS FORECASTS

I.1. Consensus predictions for posed questions

- The median consensus prediction from Metaculus of the number of new US COVID-19 hospital admissions beginning Feb 21, 2021 and ending Feb 27, 2021 is 47,000 (80% CI:[29,000, 67,000]). This aligns with the GJO consensus prediction assigning a 46% probability to fewer than 45,000 admissions and having an implied median of 46,364.
- The median consensus prediction from Metaculus of the number of new US deaths due to COVID-19 beginning Feb 21, 2021 and ending Feb 27, 2021 is 15,450 (80% CI:[10,650, 20,400]). This aligns with the GJO consensus prediction assigning a 38% proability to more than 16,000 but fewer than 18,000 deaths and having an implied median of 16,579.
- The median consensus prediction from Metaculus of the number of new US confirmed COVID-19 cases beginning Feb 21, 2021 and ending Feb 27, 2021 is 540,000 (80% CI:[300,000, 870,000]). This aligns with the GJO consensus prediction assiging a 64% probability to fewer than 600,000 cases and having an implied median of 576,188.
- The median consensus prediction from Metaculus of the cumulative number of people who will have received one of more doses of a COVID-19 vaccine in the U.S by 2021-02-28 is 55,420,000 (80% CI:[48,170,000, 68,180,000]). This aligns with the GJO consensus prediction assiging a 60% probability to between 50M and 53M doses (inclusive) and having an implied median of 52.2M.
- A consensus of experts and trained forecasters from Metaculus assigned the highest probability on the CDC monitoring 4 variants of concern by 2021-03-07. 4.0 (80% CI:[3.0, 6.0])
- The median consensus prediction from Metaculus of the percent of S-gene mutation samples that are submitted for sequencing that contain the B.1.1.7 variant between 2021-03-01 and 2021-03-07 is 42% (80% CI:[15%, 80%]).
- The median consensus prediction from Metaculus of the percent of S-gene mutation samples that are submitted for sequencing that contain the B.1.1.7 variant between 2021-03-29 and 2021-04-04 is 72% (80% CI:[43%, 95%]).

II. CONSENSUS PREDICTIVE DENSITIES FROM METACULUS

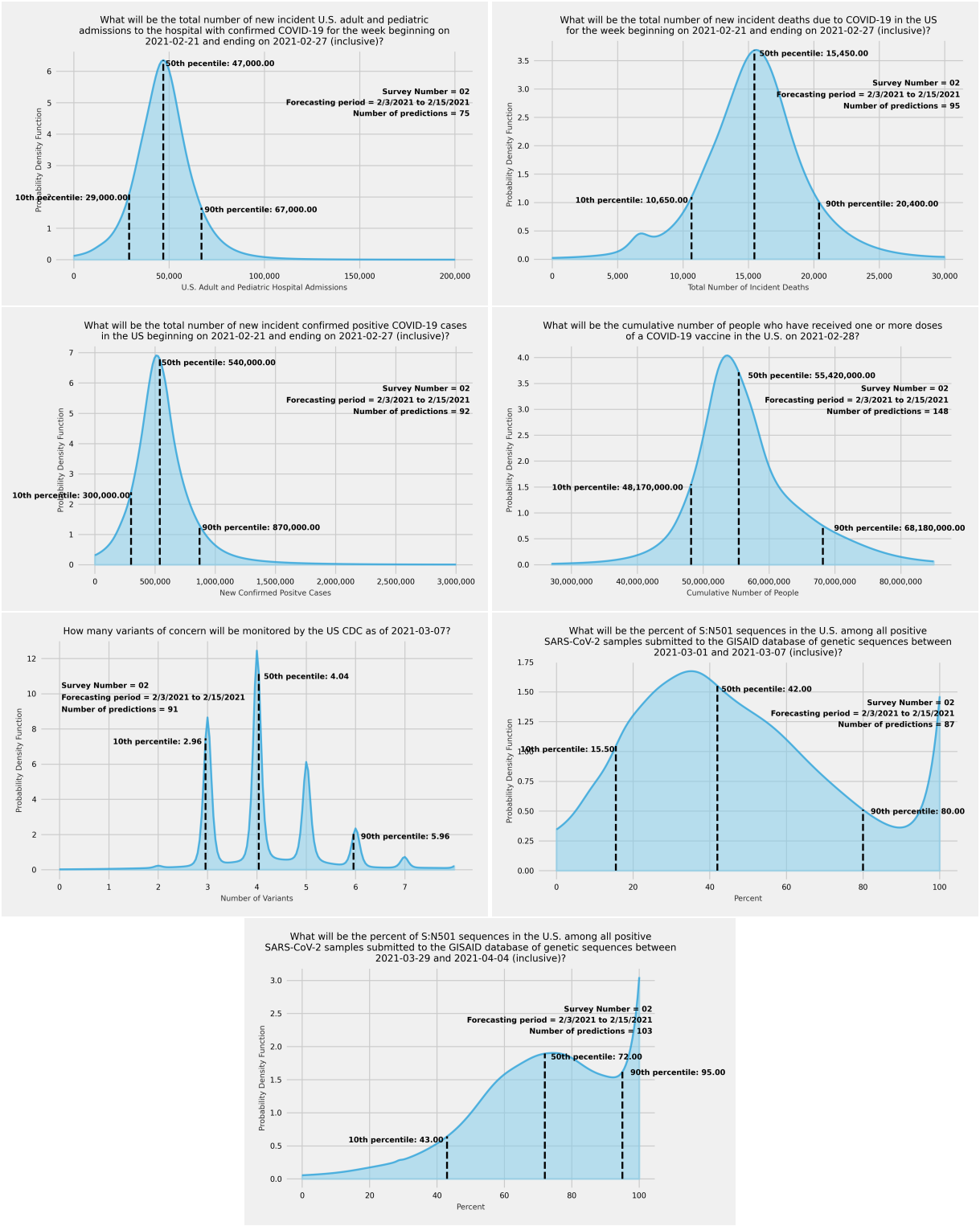

FIG. 1: Consensus predictive densities of seven targets of the US COVID-19 outbreak. A consensus density is an equally weighted average of individual densities proposed by trained forecasters and subject matter experts. Black dotted lines represent (from left to right) the tenth, fiftieth, and ninetieth percentiles of the distribution. Individual plots are available for download at https://github.com/computationalUncertaintyLab/aggStatModelsAndHumanJudgment_PUBL/tree/main/densities.

III. CONSENSUS PREDICTIVE DENSITIES FROM GOOD JUDGEMENT OPEN

GJO forecasters provided probabilities for discrete bins, which were defined in advance and in consultation with experts from Lehigh University. Over a two-week period, at least 116 individual forecasters made more than 900 discrete forecasts on four separate forecasting questions. Data from these two weeks of activity was used to build the consensus model. However, forecasters on GJO continue to update their probability judgments until the question deadline. The tables below summarize the probability judgments for each discrete bin and the implied median derived from their judgments as of February 15.

How many U.S. adult and pediatric hospital admissions with confirmed COVID-19 cases will there be for the week starting 21 February 2021?	
Fewer than 45,000	46%
Between 45,000 and 60,000 inclusive	44%
More than 60,000 but fewer than 75,000	10%
Between 75,000 and 90,000 inclusive	0%
More than 90,000 but fewer than 105,000	0%
Between 105,000 and 120,000 inclusive	0%
More than 120,000	0%
Implied median	46,364

How many deaths attributed to COVID-19 in the U.S. will be reported for the week starting 21 February 2021?	
Fewer than 14,000	4%
Between 14,000 and 16,000 inclusive	35%
More than 16,000 but fewer than 18,000	38%
Between 18,000 and 20,000 inclusive	23%
More than 20,000 but fewer than 22,000	0%
Between 22,000 and 24,000 inclusive	0%
More than 24,000	0%
Implied median	16,579

How many confirmed cases of COVID-19 in the U.S. will be reported for the week starting 21 February 2021?	
Fewer than 600,000	64%
Between 600,000 and 750,000	35%
More than 750,000 but fewer than 900,000	1%
Between 900,000 and 1,050,000 inclusive	0%
More than 1,050,000 but fewer than 1,200,000	0%
Between 1,200,000 and 1,350,000 inclusive	0%
More than 1,350,000	0%
Implied median	576,188

How many people in the U.S will have received one or more doses of a COVID-19 vaccine as of 28 February 2021, according to the CDC?	
Fewer than 50,000,000	6%
Between 50,000,000 and 53,000,000 inclusive	60%
More than 53,000,000 but fewer than 56,000,000	30%
Between 56,000,000 and 59,000,000 inclusive	4%
More than 59,000,000 but fewer than 62,000,000	0%
Between 62,000,000 and 65,000,000 inclusive	0%
More than 65,000,000	0%
Implied median	52,200,000

IV. METAFORECASTS

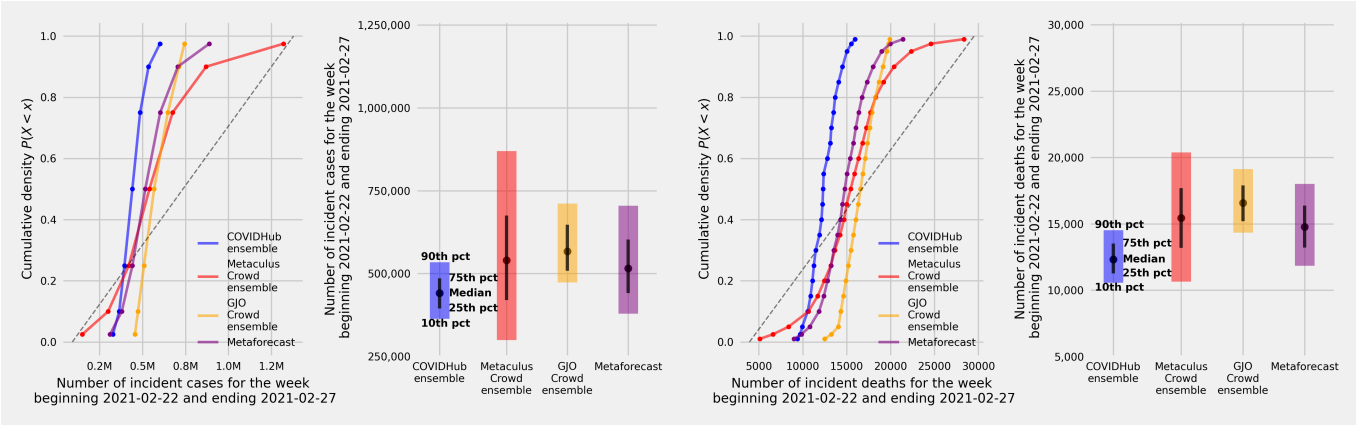

FIG. 2: Metaforecasts of the number of incident cases and incident deaths for the week beginning on Feb. 22nd, 2021 and ending on Feb 27th, 2021. A metaforecast is a combination of an ensemble of computational models from the COVID-19 Forecasthub and a consensus of predictions from trained and untrained forecasters, and experts. (A) Cumulative density functions of an ensemble of computational models, consensus of predictions from trained forecasters and experts, and a metaforecast. (B) An 80% prediction interval (the 10th and 90th percentile), 50% prediction interval (25th and 75th percentile), and the median (50th) percentile for all three ensemble models. This plot is available for download at https://github.com/computationalUncertaintyLab/aggStatModelsAndHumanJudgment_PUBL/blob/main/metaforecasts/cases_survey2.png

V. MECHANICS OF A CONSENSUS FORECAST

To build a forecast we (i) pose questions to a crowd of subject matter experts and trained generalist forecasters, (ii) collect predictive densities over potential future values from each member of the crowd, and (iii) we aggregate this set of predictive densities into a single *consensus forecast*. We expect predictions from subject matter experts and trained forecasters to be accurate and calibrated because they have access to structured data, the same data computational models use, and because they have access to subjective, unstructured data often unavailable to computational models.

Suppose we collect a set $F = \{f_1, f_2, f_3, \cdots, f_C\}$ of predictive densities from C members of the crowd. Our consensus predictive density ($f_{\text{consensus}}$) is generated as

$$f_{\text{consensus}}(v) = \sum_{i=1}^{C} \pi_i f_i(v)$$

$$\text{such that } \sum_{i=1}^{C} \pi_i = 1$$

where f_i is the ith individual density from a crowd member, C is the number of individual densities, and π_i is the corresponding weight assigned to that member of the crowd. As of now, this summary report assigns equal weights $\left(\pi_i = \frac{1}{C}\right)$ to each member who proposed a predictive density f_i

VI. MECHANICS OF A METAFORECAST

A metaforecast is built by combining an ensemble of computational models and a consensus of predictions from humans, in our case, predictions from trained forecasters and experts. The COVID-19 forecast hub ensemble cumulative

predictive density is divided into 23 quantiles for incident deaths and 7 quantiles for incident cases. We can extract the same number of quantiles from our consensus forecast and compute quantiles for our metaforecast as

$$Q_{\text{metaforecast}} = \frac{1}{3}Q_{\text{COVID-19 ensemble}} + \frac{1}{3}Q_{\text{Metaculus Consensus forecast}} + \frac{1}{3}Q_{\text{GJO Consensus forecast}}$$

where Q_x is a quantile from distribution x.

VII. ONGOING METAFORECASTING WORK

There is ongoing work to generate a full density for the meta forecast by (i) estimating a probability density for the COVID-19 ensemble from quantile information and (ii) combining predictive densities generated by the COVID-19 ensemble and consensus forecast. We plan to generate a cumulative density function (cdf) $F_{\text{COVID-19 ensemble}}$ for the COVID-19 ensemble using (i) monotic cubic interpolation [1] and (ii) fitting a mixture model that minimizes the sum square error between the fitted distribution and COVID-19 ensemble quantiles. We will combine the COVID-19 ensemble cumulative density and a linearly interpolated cumulative density from the consensus forecast as

$$F_{\text{metaforecast}}(v) = \pi_{\text{COVID-19 ensemble}}F_{\text{COVID-19 ensemble}} + \pi_{\text{Metaculus}}F_{\text{Metaculus}} + \pi_{\text{GJO}}F_{\text{GJO}}$$

where π is the weight assigned to each ensemble. We can use the linearity of the derivative and our ability to differentiate the above interpolated cdfs to generate a probability density function for the metaforecast as

$$f_{\text{metaforecast}}(v) = \frac{dF_{\text{metaforecast}}}{dv} = \pi_{\text{COVID-19 ensemble}}\frac{dF_{\text{COVID-19 ensemble}}}{dv} + \pi_{\text{Metaculus}}\frac{dF_{\text{Metaculus}}}{dv} + \pi_{\text{GJO}}\frac{dF_{\text{Metaculus}}}{dv}$$

VIII. QUESTIONS AND RESOLUTION CRITERIA

Each month, we store all question and resolution text, the launch and close data to make forecasts, and urls corresponding to question in a dataset available for download at https://github.com/computationalUncertaintyLab/aggStatModelsAndHumanJudgment_PUBL/blob/main/questions/questionData.csv.

- Question 1
  - Question: What will be the number of new incident U.S. adult and pediatric admissions to the hospital with confirmed COVID-19 for the week beginning on 2021-02-21 and ending on 2021-02-27 (inclusive)?
  - Resolution Criteria: This question will resolve as the total number of adult plus pediatric previous day admissions with confirmed COVID-19 as recorded in the Department of Health and Human Service's report of COVID-19 reported patient impact and hospital capacity for the dates from 2021-02-22 to 2021-02-28, corresponding to the number of hospitalizations from 2021-02-21 to 2021-02-27. Daily updates are provided by the Department of Health and Human Services. The total previous day admissions is computed using two variables in this report: previous_day_admission_adult_covid_confirmed and previous_day_admission_pediatric_covid_confirmed and stored in Lehigh University's Computational Uncertainty Lab Github data repository. This report, and the resolution criteria, includes data on all 50 US states, Washington DC, Puerto Rico, and the US Virgin Islands (53 states and territories). The report will be accessed no sooner than 2021-03-06.
  - Range:[0-200K]
  - Question URL Metaculus: https://pandemic.metaculus.com/questions/6468/new-us-covid-hospital-admissions-21-27-feb/
  - Question URL GJO: https://www.gjopen.com/questions/1921
- Question 2

  - What will be the total number of new incident deaths due to COVID-19 in the US for the week beginning on 2021-02-21 and ending on 2021-02-27 (inclusive)?
  - Resolution Criteria: This question will resolve as the number of new deaths due to confirmed COVID-19 for the week beginning on 2021-02-21 and ending on 2021-02-27 (inclusive) as recorded in the Johns Hopkins University (JHU) CSSE Github data repository. This file records the daily number of deaths by county. From this file deaths are summed across all counties and aggregated by week to generate the number of new deaths per week. The number of deaths for the week beginning on 2021-02-21 will be computed by adding the number of new deaths from the 2021-02-21 up to, and including, 2021-02-27. The report will be accessed no sooner than (2021-03-06).
  - Range:[0-30k]
  - Question URL Metaculus: https://pandemic.metaculus.com/questions/6466/new-us-covid-deaths-21-27-february/
  - Question URL GJO: https://www.gjopen.com/questions/1922

- Question 3
  - Question: What will be the total number of new incident confirmed positive COVID-19 cases in the US beginning on 2021-02-21 and ending on 2021-02-27 (inclusive)?
  - Resolution Criteria: This question will resolve as the number of new confirmed cases beginning on 2021-02-21 and ending on 2021-02-27 (inclusive) recorded in the Johns Hopkins University (JHU) CSSE Github data repository. This file records the daily number of cases by county. From this file cases are summed across all counties and aggregated by week to generate the number of new cases per week. The report will be accessed no sooner than 2021-03-06.
  - Range:[0-3M]
  - Question URL Metaculus: https://pandemic.metaculus.com/questions/6469/new-us-covid-cases-21-27-february/
  - Question URL GJO: https://www.gjopen.com/questions/1923

- Question 4
  - Question: What will be the cumulative number of people who have received one or more doses of a COVID-19 vaccine in the U.S. on 2021-02-28?
  - Resolution Criteria: This question will resolve as the cumulative number of people who receive one or more doses of a COVID-19 vaccine on 2021-02-28 as recorded by the Centers for Disease Control COVID-19 Data tracker in the column "Number of People Receiving 1 or More Doses." The dashboard is updated daily by 8pm ET and will be accessed on 2021-02-28 at approximately 10:00pm ET.
  - Range:[27M-85M]
  - Question URL Metaculus: https://pandemic.metaculus.com/questions/6472/cumulative-us-vaccinations-28-february/
  - Question URL GJO: https://www.gjopen.com/questions/1924

- Question 5
  - Question: How many variants of concern will be monitored by the US CDC as of 2021–03-07?
  - Resolution Criteria: This question will resolve as the number of variants of concern at the following link: "US COVID-19 Cases Caused by Variants" page as of Sunday, 2021–03-07. For example, as of 2021–02-02 this page shows that there are three variants: B.1.1.7, B.1.351, and P.1. This page is updated on Sundays, Tuesdays, and Thursdays by 7pm ET and will be accessed at approximately 10pm ET on 2021–03-07 (a Sunday).
  - Range:[0-8]
  - Question URL: https://pandemic.metaculus.com/questions/6474/-variants-monitored-by-cdc-on-7-march/

- Question 6
  - Question: What will be the percent of S:N501 sequences in the U.S. among all positive SARS-CoV-2 samples submitted to the GISAID database of genetic sequences between 2021-03-01 and 2021-03-07 (inclusive)?

- Resolution Criteria: This question will resolve as the percentage of US S:N501 sequences among all positive SARS-CoV-2 samples submitted for genomic sequencing to the GISAID database between 2021-03-01 and 2021-03-07 (inclusive), as displayed on the "Distribution of S:N501 per country" plot on following website: https://covariants.org/variants/S.N501. This website pulls data from GISAID and makes it publicly accessible. This percentage will be accessed no sooner than 2021-03-15.
- Range:[0-100]
- Question URL: https://pandemic.metaculus.com/questions/6473/-sn501-in-us-for-week-of-1-march/

- Question 7
  - Question: What will be the percent of S:N501 sequences in the U.S. among all positive SARS-CoV-2 samples submitted to the GISAID database of genetic sequences between 2021-03-29 and 2021-04-04 (inclusive)?
  - Resolution Criteria: This question will resolve as the percentage of US S:N501 sequences among all positive SARS-CoV-2 samples submitted for genomic sequencing to the GISAID database between 2021-03-29 and 2021-04-04 (inclusive), as displayed on the "Distribution of S:N501 per country" plot on following website: https://covariants.org/variants/S.N501. This website pulls data from GISAID and makes it publicly accessible. This percentage will be accessed no sooner than 2021-04-12.
  - Range:[0-100]
  - Question URL: https://pandemic.metaculus.com/questions/6477/-sn501-in-us-for-week-of-29-march/

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[1] Frederick N Fritsch and Ralph E Carlson. Monotone piecewise cubic interpolation. *SIAM Journal on Numerical Analysis*, 17(2):238–246, 1980.