

Principles of Data Science Coursework Report

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Section A

Part (a)

We begin by showing that both densities s and b are properly normalised in the range $M \in [-\infty, +\infty]$, by showing that integrating either function over this range yields a value of 1. In the former case, as a first step we use a change of variables $M = \mu + \sigma Z$ such that $\frac{dM}{dZ} = \sigma$, for which the integral limits don't change:

$$\begin{aligned}\int_{-\infty}^{\infty} s(M; \mu, \sigma) dM &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(M-\mu)^2}{2\sigma^2}\right] dM \\ &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2}Z^2\right) \cdot \sigma dZ \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{1}{2}Z^2\right) dZ \\ &=: I\end{aligned}$$

We will show that $I^2 = 1$, and since the integrand of I above is real and positive on $[-\infty, +\infty]$, this proves that $I = 1$. This requires the transformation to polar coordinates $(X, Y) = \rho(R, \phi) = (R \cos(\phi), R \sin(\phi))$ which has Jacobian matrix

$$\begin{pmatrix} \cos(\phi) & -R \sin(\phi) \\ \sin(\phi) & R \cos(\phi) \end{pmatrix}$$

and hence $|J_\rho(R, \phi)| = R$. Then,

$$\begin{aligned}
I^2 &= \frac{1}{2\pi} \left[\int_{-\infty}^{\infty} \exp(-\frac{1}{2}X^2) dX \right] \left[\int_{-\infty}^{\infty} \exp(-\frac{1}{2}Y^2) dY \right] \\
&= \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp(-\frac{1}{2}(X^2 + Y^2)) dX dY \\
&= \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\infty} \exp(-\frac{1}{2}(R^2)) \cdot R dR d\phi \\
&= \left[-\exp(-\frac{1}{2}R^2) \right]_{R=0}^{R=\infty} \\
&= 1.
\end{aligned}$$

For the background, we note that the density (the integrand) b is zero for all $M < 0$, and show

$$\begin{aligned}
\int_{-\infty}^{\infty} b(M; \lambda) dM &= \int_0^{\infty} \lambda e^{-\lambda M} dM \\
&= \left[-e^{-\lambda M} \right]_{M=0}^{M=\infty} \\
&= 1.
\end{aligned}$$

Finally this lets us show that the probability density p given is properly normalised over $[-\infty, +\infty]$ because

$$\begin{aligned}
\int_{-\infty}^{\infty} p(M; f, \lambda, \mu, \sigma) dM &= f \int_{-\infty}^{\infty} s(M; \mu, \sigma) dM + (1 - f) \int_{-\infty}^{\infty} b(M; \lambda) dM \\
&= f \cdot 1 + (1 - f) \cdot 1 \\
&= 1.
\end{aligned}$$

Part (b)

In order to ensure that the fraction of signal in the restricted distribution for M remains f , we must normalise the signal and background separately over $[\alpha, \beta]$. We introduce these new restricted distributions as

$$s_r(M; \mu, \sigma) = \frac{s(M; \mu, \sigma)}{\int_{\alpha}^{\beta} s(M; \mu, \sigma) dM} \quad b_r(M; \lambda) = \frac{b(M; \lambda)}{\int_{\alpha}^{\beta} b(M; \lambda) dM}$$

We then compute the relevant integrals:

$$\begin{aligned} \int_{\alpha}^{\beta} s(M; \mu, \sigma) dM &= \int_{-\infty}^{\beta} s(M; \mu, \sigma) dM - \int_{-\infty}^{\alpha} s(M; \mu, \sigma) dM \\ &= \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\beta - \mu}{\sigma \sqrt{2}} \right) \right] - \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\alpha - \mu}{\sigma \sqrt{2}} \right) \right] \\ &= \frac{1}{2} \operatorname{erf} \left(\frac{\beta - \mu}{\sigma \sqrt{2}} \right) - \frac{1}{2} \operatorname{erf} \left(\frac{\alpha - \mu}{\sigma \sqrt{2}} \right) \end{aligned}$$

where the error function erf is defined for any argument x as

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt,$$

and for the background,

$$\begin{aligned} \int_{\alpha}^{\beta} b(M; \lambda) dM &= \int_{-\infty}^{\beta} b(M; \lambda) dM - \int_{-\infty}^{\alpha} b(M; \lambda) dM \\ &= 1 - e^{-\lambda \beta} - (1 - e^{-\lambda \alpha}) \\ &= e^{-\lambda \alpha} - e^{-\lambda \beta} \end{aligned}$$

The properly normalised probability density function for $M \in [\alpha, \beta]$ is then

$$p_r(M; \boldsymbol{\theta}) = \frac{2f}{\operatorname{erf} \left(\frac{\beta - \mu}{\sigma \sqrt{2}} \right) - \operatorname{erf} \left(\frac{\alpha - \mu}{\sigma \sqrt{2}} \right)} s(M; \mu, \sigma) + \frac{1 - f}{e^{-\lambda \alpha} - e^{-\lambda \beta}} b(M; \lambda) \quad (1)$$

where $s(M; \mu, \sigma)$ and $b(M; \lambda)$ are as given on the sheet. Note that the value for $p_r(M; \boldsymbol{\theta})$ is zero when $M \notin [\alpha, \beta]$.

Part (c)

To implement the expressions for the probability density function, the following function was used.

```
1  def pdf_norm_expon_mixed(x, f, la, mu, sg, alpha, beta):
2      # Compute the value signal and background PDF values
      without
3      # truncating to [alpha, beta].
4      pdf_s = norm.pdf(x, loc=mu, scale=sg)
5      pdf_b = expon.pdf(x, loc=0, scale=1 / la)
6      # Compute the PDF value weights, including the signal
      fraction f
7      # and normalising to the interval.
8      weight_s = (2 * f) / (
9          erf((beta - mu) / (sg * np.sqrt(2)))
10         - erf((alpha - mu) / (sg * np.sqrt(2)))
11     )
12     weight_b = (1 - f) / (np.exp(-la * alpha) - np.exp(-la *
13         beta))
14     return (weight_s * pdf_s) + (weight_b * pdf_b)
```

Listing 1: Function implementing PDF for part (c).

The function takes in the argument `x`, the four parameters `f`, `la`, `mu`, `sg` corresponding to f, λ, μ, σ respectively, and `alpha`, `beta` which represent the support $[\alpha, \beta]$. The function first computes the signal and background parts of the density as specified by $s(\cdot)$ and $b(\cdot)$, without any domain restriction. This is done with the `norm.pdf` and `expon.pdf` from the `numba_stats` package. Next we compute the coefficients of these terms as specified in (1) using the `scipy.special` module to evaluate the error function, using its method `erf`. Finally we return the weighted sum of the two PDF evaluations to give the mixed PDF value at `x`.

We also check this function is properly normalised in the interval $[5, 5.6]$ using the following code.

```
1  def check_normalisation(pdf, lower, upper):
2      integral_value, abserr = quad(pdf, lower, upper)
3      return integral_value
```

Listing 2: Function checking the normalisation of the PDF for part (c).

This code uses the `quad` method from `scipy.integrate` to integrate any function `pdf` over the given range specified by `lower`, `upper`. The script `solve_part_c.py` prints the output of this function for three different pa-

parameter settings with the interval $[5, 5.6]$; the outputs should all read as approximately unity to many decimal places.

Part (d)

In Figure 1 we see the underlying probability density function for M , which we will sample from later.

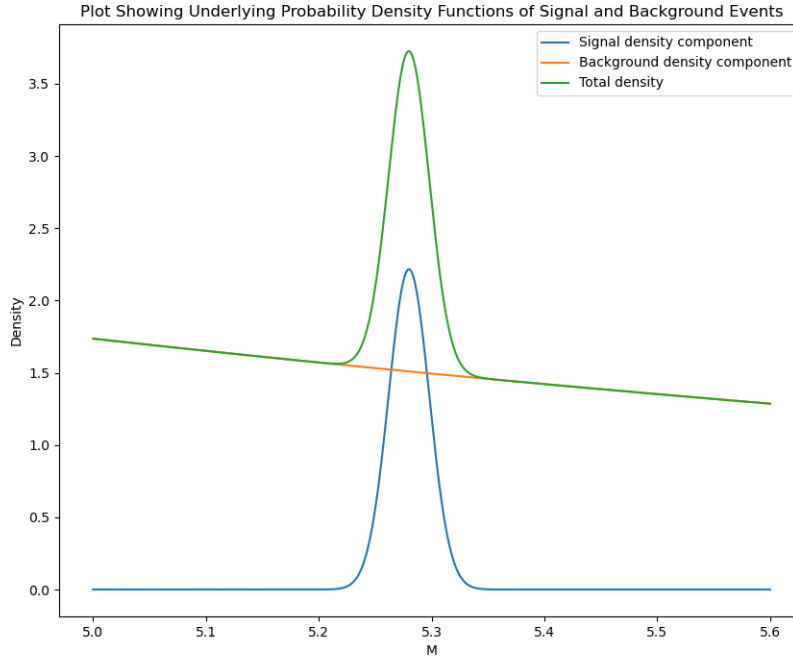


Figure 1: The true underlying distribution of M [generated in Python using Matplotlib].

Note that the blue and orange lines, labelled as ‘density components’ indicate the shape of the probability density functions for M for the signal and background events respectively. However, neither is technically a true density function; both of them have been multiplied by the respective prevalence of signal and background events in the population distribution. The area under either of the component functions limited to an interval smaller than $[5, 5.6]$

is precisely the probability that an event randomly sampled from the whole population will be of that kind (signal or background), and lie within said interval.

Part (e)

Originally, rejection sampling was used to sample from the signal plus background distribution, but this was found to be quite slow, a problem which was exacerbated in the simulation studies. Instead, an inverse CDF method was implemented. The inverse CDF method involves generating a sample of points uniformly distributed in $[0, 1]$, and then transforming these by the percentage point function of the desired distribution.

Let X have distribution $U(0, 1)$, and denote the transformed random variable $Y := F^{-1}(X)$ where F is the CDF of the distribution we wish to sample from. Then clearly Y has the desired distribution because for any $c \in (-\infty, +\infty)$,

$$\begin{aligned} P(Y \in (-\infty, c)) &= P(F^{-1}(X) \in (-\infty, c)) \\ &= P(X \in (0, F(c))) && F \text{ is monotonic and increasing} \\ &= F(c) && X \text{ is uniformly distributed} \end{aligned}$$

Hence Y has CDF F , proving that the transformed data points should have the desired distribution. In this case the cumulative distribution for the true density p is intractable, and thus we have to estimate it at small discrete intervals using the below block of code.

```

1  # Compute CDF values across interval [5.0, 5.6].
2  cdf_mixed_approx_sb = cdf_norm_expon_mixed(
3      input_space, 0.1, 0.5, 5.28, 0.018, 5.0, 5.6
4  )
5  quantiles_sb = np.linspace(0.0, 1.0, int(10**GRANULAR))
6  cdf_mixed_inv_sb_01 = np.zeros(int(10**GRANULAR))
7  # For each quantile in [0.0, 1.0], find how far into the
   range [5.0, 5.6] you
8  # need to go in order for the CDF to equal the quantile.
9  for quantile_idx, quantile in enumerate(quantiles_sb):
10     cdf_mixed_inv_sb_01[quantile_idx] = (10 ** (-GRANULAR))
   * np.sum(
11     cdf_mixed_approx_sb < quantiles_sb[quantile_idx]
```

```

12     )
13     # Transform into the interval [5.0, 5.6].
14     CDF_MIXED_INV_APPROX_SB = 5.0 + 0.6 * cdf_mixed_inv_sb_01
15

```

Listing 3: Code block producing array of values for inverse CDF of p (e).

| Parameter | Estimate | Error Estimate |
|-----------|----------|----------------|
| f | 0.0998 | 0.0016 |
| λ | 0.505 | 0.019 |
| μ | 5.28014 | 0.00033 |
| σ | 0.01787 | 0.00032 |

Table 1: Estimates produced by Minuit package.

| cov(,) | f | λ | μ | σ |
|-----------|-----------|-----------|-----------|-----------|
| f | 2.67e-06 | -3.45e-07 | -8.74e-09 | 2.38e-07 |
| λ | -3.45e-07 | 0.000373 | 2.81e-07 | -5.07e-08 |
| μ | -8.74e-09 | 2.81e-07 | 1.08e-07 | -2.39e-09 |
| σ | 2.38e-07 | -5.07e-08 | -2.39e-09 | 1.00e-07 |

Table 2: Matrix of covariances of parameter estimates.

We then model the density function of the sample parametrically using a model of the same form as the true distribution p . The four parameters are estimated by using a binned maximum likelihood procedure: first separating the data into 100 bins, and then finding maximum likelihood estimates for the parameters based on the binned data. This is done using the `iminuit` Python package.

In Table 1 we see the fitted values for the binned maximum likelihood fit for the large sample run in `solve_part_e.py`. We see that the parameter estimates are very close to their true values, with correspondingly low errors. Table 2 gives more information about the errors, displaying the matrix of covariances between the parameter estimates.

The `iminuit` package produces this estimate of the covariances by estimating the inverse of the Hessian of the negative log-likelihood function [1]. The errors in Table 1 are then the square roots of the variances (diagonal entries), that is, estimates of the uncertainties of the estimates. These estimates rely on the assumption of a large sample size (which is true in this case)

and that the second derivatives of the log-likelihood are relatively constant near the true maximum-likelihood estimate.

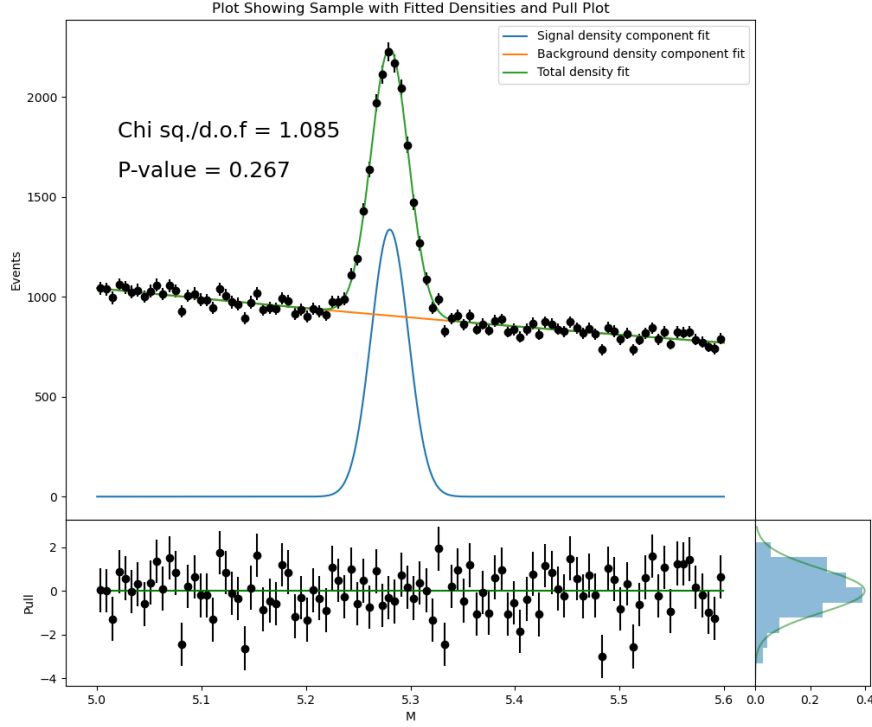


Figure 2: Plot showing sample bins and fitted density [generated in Python using Matplotlib].

The sample is plotted along with its fitted density according to the parameter estimates in Figure 2. Since the sample is binned, each of the bin counts is treated as a Poisson random variable and hence the errors plotted are the square roots of the bin counts. Below the main plot, we have a plot of the ‘pull’ values; the residual errors of the bin counts versus the fitted model, divided by the bin errors. The histogram to the right confirms that these values appear to follow a standard Gaussian distribution (the green line) which is to be expected because the density that has been fitted has the correct functional form. Moreover, the χ^2 value, the sum of the squares of the pulls,

is approximately equal to the number of degrees of freedom, 95, indicating that we have produced a high quality fit, whilst avoiding overfitting to the noise of the sample.

Section B

Part (f)

For this section, the statistical analysis examines the null hypothesis H_0 that there is no signal present in the data, that is, $f = 0$, and the alternative hypothesis H_1 , that there is at least one signal event, $f \in (0, 1]$. The procedure is outlined in the next section.

Procedure for Simulation Study to Compute Rate of Discovery of Signal Events

1. Throw a toy, generating a sample \vec{x} of size N from the true distribution.
2. Use binned maximum likelihood estimation to fit the parameters under the H_0 model, fixing $f = 0$, and obtaining likelihood $L(\vec{x}|H_0)$.
3. Use binned maximum likelihood estimation to fit the parameters under H_1 with all parameters floating, to obtain $L(\vec{x}|H_1)$.
4. Compute the log-likelihood ratio statistic, $T = 2 \ln(L(\vec{x}|H_1)/L(\vec{x}|H_0))$.
5. Repeat steps 1-4 for a toy generated from the background only distribution.
6. Repeat steps 1-5 for a high number of toys, N_{toys} , to produce samples of the log-likelihood ratio under H_0 and H_1 .
7. Use this to compute the discovery rate at a significance level of 2.9×10^{-7} .

Steps 2-4 detail the standard statistical procedure that could be used to infer the presence of signal in the given sample, in the realistic setting of an experiment.

However, this relies on having some critical value for the test statistic which we do not have for the statistical model. Hence steps 5-7 are used to

simulate a large number of ‘toys’, datasets independently sampled from the true distribution to estimate the distribution of T under H_1 , and similarly for the distribution under H_0 . The two distributions then enable us to set a critical value $T = T_0$ for discovery according to the specified significance, and to find the resulting statistical power of the test. In particular, we have

$$\text{significance} = P(T > T_0 | H_0) = 2.9 \times 10^{-7} \quad (2)$$

$$\text{power} = P(T > T_0 | H_1) \quad (3)$$

Equation (2) fixes the value of T_0 , above which the test statistic provides evidence for a scientific discovery of at least one signal event, in which case we reject the null hypothesis in favour of the alternate hypothesis. Equation (3) tells us the statistical power of this test. With the desired power, 90%, the probability of falsely rejecting the alternative hypothesis when it is true is 10%. In our context, we are indeed assuming that the true population distribution satisfies the alternative hypothesis, and so the power is equivalent to the rate of discovery of the true signal from the sample. In other words, under repeated samples of the given size, we would expect to claim a discovery (with $T > T_0$) in 90% of such samples.

Therefore the discovery rate is a function of the sample size N used. As N increases, the two distributions of T become more distinct, as the estimates of the parameters have decreased uncertainty. In turn, the discovery rate at the 5 standard deviation significance level increases since a greater proportion of the true distribution of T lies above the T_0 . Hence we run the procedure above for a range of N values until we find the correct value to achieve a 90% discovery rate.

One of the serious challenges of this simulation study is that T_0 is supposed to lie at an extremely high quantile of the distribution of T under the null hypothesis. Therefore, in order to precisely locate T_0 , we would ideally produce a sample of T with size $\sim 10^8$ in order to ensure that the empirical distribution was based on a sample actually containing some points above the 5 standard deviation quantile. A lot of time was spent optimising the code in order to achieve this end, but it proved impossible with the given processing and time constraints.

Therefore, the solution was to perform the study with a much smaller number of toys thrown to find T , around $\sim 10^5$ at most, and then use this to parametrically estimate the true distribution under H_0 . Theoretically, Wilks’ Theorem [2] provides an asymptotic result which ensures that as N

approaches infinity, twice the negative log-likelihood ratio follows a χ^2 distribution under the null hypothesis, under certain regularity conditions, such as the null hypothesis being simple, the alternate being composite, and the former being a subset of the latter. Moreover, in this case the degrees of freedom of the χ^2 distribution should be the difference in dimension of the two spaces of parameters for the hypotheses. In our context some of the regularity conditions have been violated, for instance our null hypothesis $f = 0$ lies on the boundary of the parameter space for H_1 . However, in many cases such as this one, it has been found that the null hypothesis distribution of T still loosely follows some form of χ^2 distribution, often just with a different degrees of freedom parameter, or a mixture of multiple χ^2 distributions [3] [4]. Therefore we overcome the small number of toys used by fitting a χ^2 model to the sample of T distributed under H_0 , and using this estimate to find the value of T_0 at the required significance level.

In order to find the appropriate trade-off between processing time and precision, a preliminary scan of different values of N was performed over a large range of N values, and using a small number of toys, 1000. This gave an indication of the approximate critical value of N . Then a second simulation study was performed with a much narrower range of sample size values, but using 10000 toys in each case. These results are recorded in Tables 3 and 4.

In all cases, the `iminuit` package was used to fit the parameter estimates, and give the estimated errors of these fits. In the simple cases of fitting the background only model to data sampled from the background only distribution, and similarly for the mixed model, the coverage of the fitted parameters with respect to the true values was computed, in order to check that the fits used for the study were of high quality. The `iminuit` package also reports whether or not a valid minimum was reached. If either of the two fits associated to a generated T value were invalid, then that T value was discarded and not used in the study. In all the results the proportion of valid T values (recorded in the ‘Valid’ column) was sufficiently high that the number of toys used was close to the specified amount. In addition, with the exception of apparent overcoverage in the case of very low sample sizes N in Table 3, we can see that the coverages for the estimates checked when fitting H_0 and H_1 were close to the expected 68.3%.

In Table 4 we see that the critical value to achieve 90% power is somewhere in the range $N = 705$ and $N = 710$; interpolating linearly we estimate that 707 data points are required for a 90(.0036)% discovery rate, according to our simulation using 10000 toys.

| N | C. H1 | C. H0 | Valid | T0 | Power |
|------|-------|-------|-------|--------|----------|
| 50 | 0.767 | 0.794 | 0.749 | 30.294 | 0.000000 |
| 100 | 0.785 | 0.805 | 0.861 | 32.335 | 0.001161 |
| 150 | 0.774 | 0.805 | 0.942 | 28.608 | 0.012739 |
| 200 | 0.762 | 0.793 | 0.947 | 31.993 | 0.027455 |
| 250 | 0.721 | 0.781 | 0.974 | 31.331 | 0.088296 |
| 300 | 0.691 | 0.744 | 0.973 | 31.940 | 0.169579 |
| 350 | 0.653 | 0.730 | 0.983 | 31.198 | 0.291963 |
| 400 | 0.654 | 0.707 | 0.980 | 30.746 | 0.430612 |
| 450 | 0.652 | 0.704 | 0.988 | 31.058 | 0.537449 |
| 500 | 0.655 | 0.695 | 0.986 | 32.214 | 0.598377 |
| 550 | 0.653 | 0.691 | 0.986 | 31.666 | 0.716024 |
| 600 | 0.650 | 0.689 | 0.988 | 31.821 | 0.782389 |
| 650 | 0.655 | 0.684 | 0.990 | 31.538 | 0.856566 |
| 700 | 0.654 | 0.688 | 0.987 | 32.286 | 0.893617 |
| 750 | 0.671 | 0.676 | 0.988 | 31.110 | 0.935223 |
| 800 | 0.659 | 0.672 | 0.982 | 32.073 | 0.949084 |
| 850 | 0.661 | 0.665 | 0.988 | 31.483 | 0.971660 |
| 900 | 0.663 | 0.662 | 0.988 | 32.212 | 0.978745 |
| 950 | 0.663 | 0.673 | 0.987 | 32.675 | 0.985816 |
| 1000 | 0.671 | 0.664 | 0.991 | 31.250 | 0.992936 |

Table 3: Preliminary simulation study for part (f) using 1000 toys in each case.

| N | C. H1 | C. H0 | Valid | T0 | Power |
|-----|-------|-------|-------|--------|----------|
| 700 | 0.654 | 0.685 | 0.985 | 31.669 | 0.893198 |
| 705 | 0.655 | 0.687 | 0.986 | 31.779 | 0.897272 |
| 710 | 0.660 | 0.683 | 0.985 | 31.578 | 0.904182 |
| 715 | 0.659 | 0.684 | 0.987 | 31.617 | 0.906548 |
| 720 | 0.655 | 0.680 | 0.985 | 31.788 | 0.909063 |
| 725 | 0.658 | 0.682 | 0.986 | 31.799 | 0.912854 |
| 730 | 0.661 | 0.682 | 0.986 | 31.679 | 0.916819 |
| 735 | 0.660 | 0.684 | 0.986 | 31.888 | 0.916607 |
| 740 | 0.661 | 0.684 | 0.988 | 31.746 | 0.921785 |
| 745 | 0.660 | 0.684 | 0.986 | 32.016 | 0.922203 |
| 750 | 0.663 | 0.685 | 0.984 | 31.744 | 0.927548 |

Table 4: Second simulation study for part (f) using 10000 toys in each case.

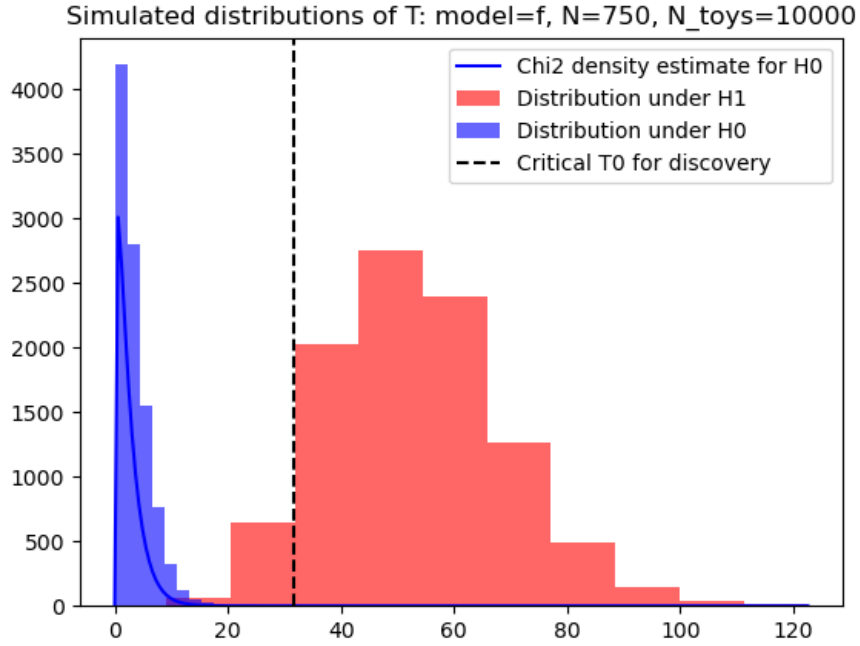


Figure 3: Simulations of the test statistic for part (f) [generated in Python using Matplotlib].

The χ^2 distribution fitted to T under H_0 was found to have an average of 2.5 degrees of freedom across all of the fits that used 10000 toys. Figure 3 shows the two generated distributions for T , as well as this χ^2 fit to the H_0 distribution. The χ^2 density shown does not fit the distribution perfectly, as it seems to underestimate the counts of the bins for the empirical distribution. However, even with 10000 toys generated, it should be noted that the expected number of T values above the 5 standard deviation quantile of the true distribution, is much less than 1 (around 0.03). Therefore, the χ^2 fit still represents an improvement on simply using the empirical quantiles since this would massively underestimate both the critical value of T_0 , and hence the sample size needed.

Part (g)

The first step in investigating the two versus one signal context was to implement a function to evaluate the CDF of the two-signal model, as well as the inverse CDF sampling from this model.

In turn, the same procedure used to investigate the discovery rate for part (f) was used for this context as well. The difference was that now the model being fit was,

$$p(M) = f_1 s_1(M; \mu_1, \sigma) + f_2 s_2(M; \mu_2, \sigma) + (1 - f_1 - f_2) b(M; \lambda).$$

and the two hypotheses were changed such that in H_1 , all parameters simply belonged to their physical parameter space:

$$(f_1, f_2) \in \{(a, b) : a \geq 0, b \geq 0, a + b \leq 1\};$$

$$\mu_1, \mu_2 \in [5.0, 5.6];$$

$$\lambda, \sigma > 0.$$

while H_0 was the subset of H_1 with the restriction $f_2 = 0$, so that there is just one signal.

As before, a preliminary search of the values of N was performed, with results in Table 5. This was followed by a further search of the range $N = 2550$ to $N = 2650$, with results in Table 6.

The fitted degrees of freedom parameter for the test statistic under the null hypothesis was very stable, found to be 1.0 to 1 decimal place in every

| N | C. H1 | C. H0 | Valid | T0 | Power |
|------|-------|-------|-------|--------|----------|
| 2000 | 0.669 | 0.670 | 0.992 | 26.672 | 0.650202 |
| 2050 | 0.673 | 0.676 | 0.992 | 27.078 | 0.664315 |
| 2100 | 0.672 | 0.682 | 0.993 | 26.745 | 0.709970 |
| 2150 | 0.680 | 0.678 | 0.993 | 26.495 | 0.746224 |
| 2200 | 0.678 | 0.678 | 0.994 | 26.384 | 0.768612 |
| 2250 | 0.679 | 0.680 | 0.995 | 26.359 | 0.798995 |
| 2300 | 0.678 | 0.679 | 0.995 | 26.487 | 0.807035 |
| 2350 | 0.682 | 0.680 | 0.995 | 26.402 | 0.838191 |
| 2400 | 0.682 | 0.678 | 0.992 | 26.990 | 0.833669 |
| 2450 | 0.675 | 0.679 | 0.989 | 26.816 | 0.862487 |
| 2500 | 0.676 | 0.680 | 0.991 | 26.527 | 0.887992 |
| 2550 | 0.675 | 0.678 | 0.988 | 26.651 | 0.899798 |
| 2600 | 0.679 | 0.679 | 0.997 | 26.552 | 0.912738 |
| 2650 | 0.679 | 0.679 | 0.992 | 26.689 | 0.923387 |
| 2700 | 0.678 | 0.679 | 0.991 | 26.414 | 0.935419 |
| 2750 | 0.673 | 0.681 | 0.990 | 26.310 | 0.941414 |
| 2800 | 0.677 | 0.683 | 0.993 | 26.439 | 0.945619 |
| 2850 | 0.677 | 0.686 | 0.996 | 26.038 | 0.950803 |
| 2900 | 0.676 | 0.683 | 0.995 | 26.506 | 0.952764 |
| 2950 | 0.676 | 0.683 | 0.994 | 26.396 | 0.960765 |
| 3000 | 0.671 | 0.682 | 0.991 | 26.314 | 0.963673 |

Table 5: First simulation study for part (g) using 1000 toys in each case.

| N | C. H1 | C. H0 | Valid | T0 | Power |
|------|-------|-------|-------|--------|----------|
| 2550 | 0.678 | 0.676 | 0.993 | 26.233 | 0.890126 |
| 2570 | 0.679 | 0.677 | 0.993 | 26.223 | 0.895762 |
| 2590 | 0.679 | 0.678 | 0.992 | 26.193 | 0.900851 |
| 2610 | 0.679 | 0.679 | 0.994 | 26.141 | 0.904987 |
| 2630 | 0.680 | 0.678 | 0.992 | 26.121 | 0.909893 |
| 2650 | 0.679 | 0.677 | 0.993 | 26.143 | 0.913779 |

Table 6: Second simulation study for part (g) using 20000 toys in each case.

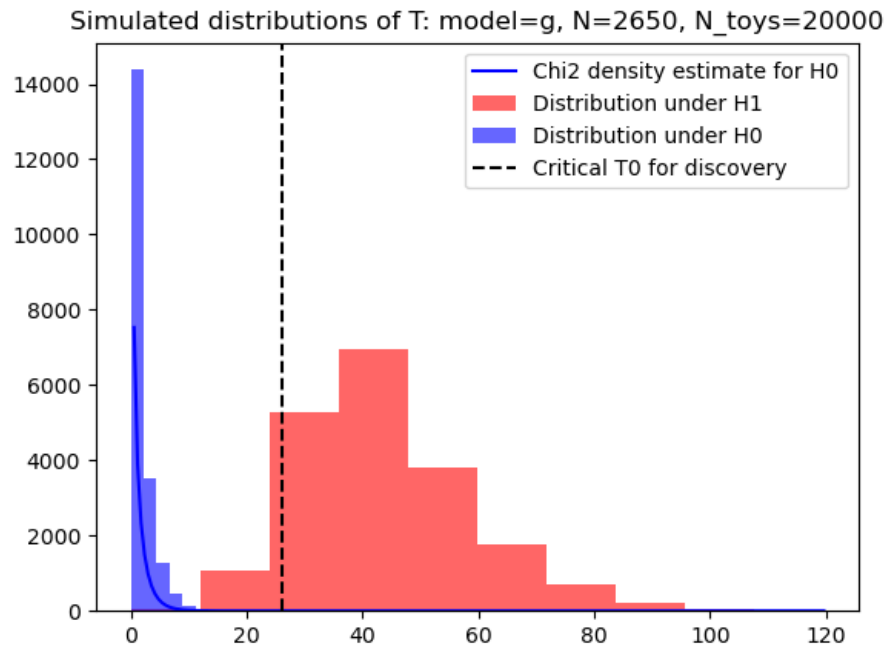


Figure 4: Simulations of the test statistic for part (g) [generated in Python using Matplotlib].

case. We can see again (Figure 4) that although the χ^2 fit for the null hypothesis distribution does not match the bins perfectly, it clearly increases the empirical ‘ 5σ ’ quantile of the simulation by a reasonable amount to ensure we do not underestimate the necessary sample size. The second simulation study in this case could not achieve the same precision as that of part (f); using a finer step size for N or only 10000 toys as before led to a series of discovery rates that did not monotonically increase with N . This is likely an artefact of the less stable maximum likelihood fitting procedure in this case, given that more parameters needed to be estimated than in part (f). Nonetheless, we can linearly interpolate within the interval 2570 to 2590 and find that the estimated critical value was $N = 2587$; this is approximately the minimum sample size necessary for a 90% discovery rate.

References

- [1] Hans Dembinski and Piti Ongmongkolkul et al. scikit-hep/iminuit. Dec 2020.
- [2] Samuel S. Wilks. The Large-Sample Distribution of the Likelihood Ratio for Testing Composite Hypotheses. *The Annals of Mathematical Statistics*, 9(1):60 – 62, 1938.
- [3] Sara Algeri, Jelle Aalbers, Knut Dundas Morå, and Jan Conrad. Searching for new phenomena with profile likelihood ratio tests. *Nature Reviews Physics*, 2(5):245 – 252, April 2020.
- [4] Herman Chernoff. On the Distribution of the Likelihood Ratio. *The Annals of Mathematical Statistics*, 25(3):573 – 578, 1954.

README File Contents

Principles of Data Science Coursework Repository

Description

This repository contains code that is used to statistically investigate an experiment in which we are interested in discovering signal events from a sample of events with associated random variable M .

The functionality enables users to sample from a mixed distribution where the background events are modelled as having an exponential distribution in M , whereas the value of M for the signal events is a narrow spike around some critical value, modelled as a Gaussian distribution. Further functions enable users to estimate the sample size required to achieve a discovery rate of 90

How to use the project

The project is designed to be usable via Docker. In order to run the project in this way, it is best to clone the repository to your local device using git, build the docker image using the terminal command

```
docker build -t s1_jh2284 .
```

and then running the container by executing the command

```
docker run --rm -ti s1_jh2284
```

where the options specify that the container is removed after exiting, and ensure that the container can be interacted with easily in the terminal. Alternatively, you can run (in the root directory)

```
conda env create -f environment.yml
```

```
conda activate mphildis_assessment_jh2284
```

to build the correct conda environment and run the code in the location you cloned it to. Next, to run the actual code you simply execute the command

```
python src/solve_part-[c-g].py
```

The codebase is highly modular in order to make the individual scripts more readable, and to have less duplicated code. The scripts for parts c and d use routines created in `mixed_pdf_tools`, while the scripts for the rest of the questions use more advanced routines in `simulation_tools`. In particular, this module initialises the global variables used for the inverse CDF sampling

whenever they are imported, so you may notice a brief delay of around 30 seconds when running the scripts for parts e-g.

Computer specification details

The repository was developed on a system with specifications

- Processor: Intel(R) Core(TM) i5-1035G1 CPU @ 1.00GHz, 1190 Mhz, 4 Core(s), 8 Logical Processor(s)
- Installed Physical Memory (RAM): 8.00 GB

The following gives approximate execution times using this system:

- `python src/solve_part_c.py` 5 secs
- `python src/solve_part_d.py` 5 secs
- `python src/solve_part_e.py` 30 secs
- `python src/solve_part_f.py` 40 mins
- `python src/solve_part_g.py` 2 hrs
- `docker build -t s1_jh2284 .` 5 mins