Problem Chosen	2022 MCM/ICM Summary Sheet	Team Control Number
C		2227952

Bitcoin and gold are both fungible stores of value. Beyond that, they could not be more different. Humans have used gold as a store of value for millennia, whereas Bitcoin (BTC) served as a currency for the first time on 22 May 2010 when Laszlo Hanyecz bought two pizzas for 10,000 BTC. We found that gold's maturity and bitcoin's immaturity translated to their market behavior. Our best predictions, in terms of mean absolute percentage error (MAPE), for Bitcoin price came from a short-sighted ARIMA(1,1,1) [Autoregressive(1 day back) integrated(1 day back) moving average(1 day back)] model. Predictions for gold preferred the less volatile ARIMA(4,1,0) model. We preferred ARIMA models to black-box alternatives, such as LSTM (Long short-term memory) models, since our chosen trading strategy depends on the ARIMA models' 30-day forecasts and standard errors rather than just the predictions themselves.

While we found bitcoin an asset worthy of investment, its notorious volatility merits a risk-aware trading strategy. Going all-in on bitcoin whenever predictions suggest it will spike may perform the best on expectation but may lead to devastating single-day losses that can push away clients, or worse, bring forward their lawyers. Therefore, we balance performance and risk level in selecting an agent-based approach, in which our portfolio is divided among 49 algorithmic agents evenly each day. Each agent has a unique perspective on risk — one agent aggressively trades gold while conservatively gauging the risk of bitcoin, while another agent does the reverse. Agents measure risk in terms of our predictions' standard errors, so when an asset becomes more volatile, all but the most aggressive agents treat it more cautiously.

Trading fees initially stiffened agents' willingness to make trades, so we allowed agents to use the ARIMA models' 30-day forecasts to justify the fees. Our risk-aware strategy paid off, building a starting portfolio of $1000 up to a final portfolio of net worth $63,147 while never falling below $929.

Using our model to determine agents' actions, we observed that our strategy suggests the action "hold" more significantly than any other action. Based on the real value of bitcoin over the given time period, we understand that choosing to hold is the best strategy to maximize net worth. Among all suggested trading actions, buying bitcoin is considered the top choice during the given trading period. The result of sensitivity analysis shows that our trading strategy is sensitive to dramatic changes (0.075%, 0.075%) in transaction costs and performs relatively well when the fees are either doubled or halved from the standard range (2%, 1%).

Trading Strategies: How Bitcoin & Gold Rise and Fall Throughout Time

2227952

Contents

1 Background Information

We have been asked by a trader to develop a model that uses only the past stream (September 11th, 2016, to September 10th, 2021) of daily prices for bitcoin and gold to determine each day if they should buy, hold, or sell their assets in their portfolio. To do this, we needed to first research bitcoin and gold to learn information such as what factors influence their prices on a day-to-day basis. We also needed to research trading strategies, specifically daily trading strategies that we could reflect in our model.

1.1 What Influences Bitcoin?

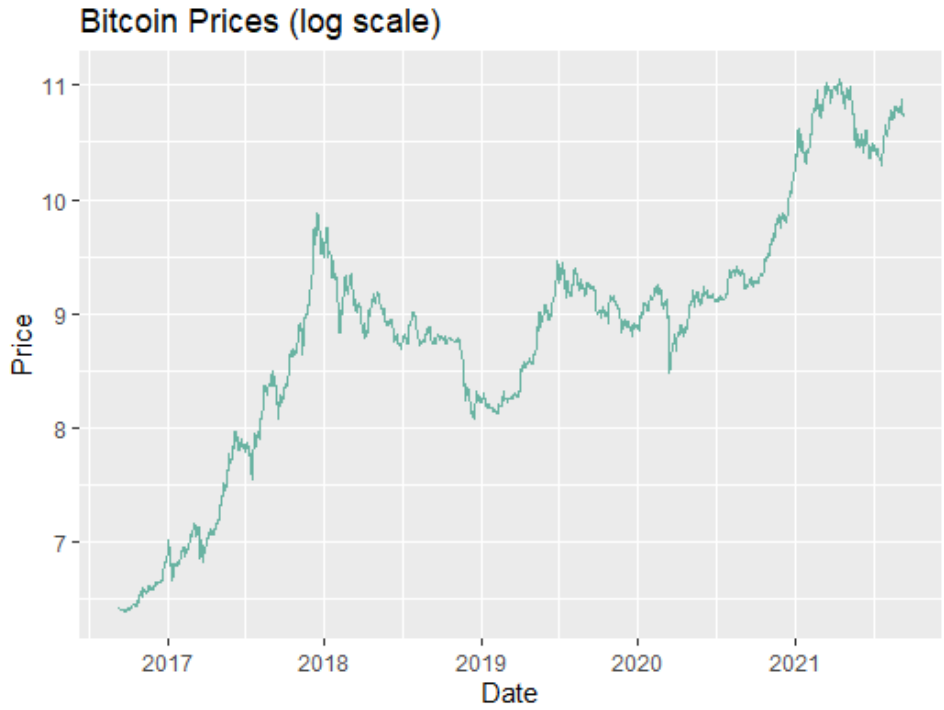


Figure 1: Bitcoin price vs Date (9/11/2016-9/10/2021)

To best make predictions on whether to buy, hold, or sell bitcoin on a daily basis we needed to understand what factors influence bitcoin's price fluctuations. Upon thorough research, we found that numerous factors influenced these fluctuations ranging from supply and demand to the media and influential people.

Supply and Demand

Just like almost everything that can be bought, sold, and traded around the world, bitcoin is influenced by supply and demand. It is well-known that goods limited to a certain total (especially a low total) have higher prices. Bitcoin is limited to twenty-one million coins. So, the closer the supply gets to this number, the higher the prices will be. In the same way, as demand for bitcoin increases, so does its price. On the other hand, as demand for bitcoin decreases, so does its price. [10]

Investor Influences

Since bitcoin has seen a trend of price increase over time, many wealthy, long-term investors hold onto their bitcoin for months to years. This makes it difficult for less wealthy investors to attain exposure to bitcoin. In addition, reputable investors tend to influence the market with their actions. If reputable investors suddenly sell their shares, bitcoin prices would rapidly decline as many small investors follow the trends of large investors.

Bitcoin in the Media

Most people are aware that not everything in the media is true. With bitcoin, it is the same trend. Many media outlets share information about bitcoin that is not always backed up by evidence. This leads to many investors buying and selling when they should be doing the opposite or holding. In addition, many influential people share their opinions through the media. If a long-term, wealthy investor announces they are buying or selling, many people who look up to these people will follow. [10]

1.2 What Influences Gold?

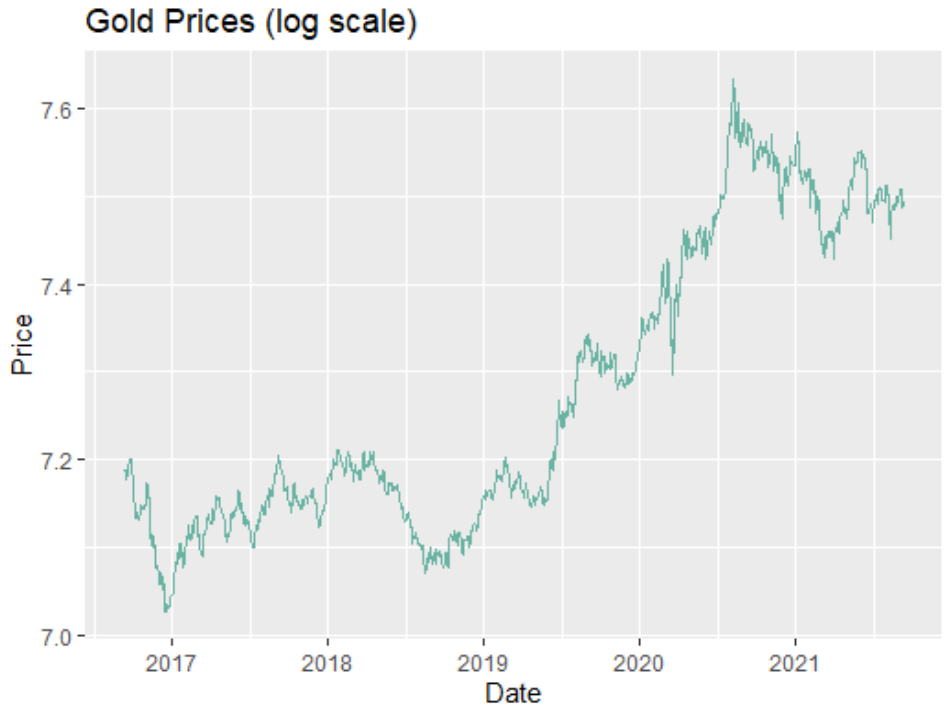


Figure 2: Gold Price vs Date (9/11/2016-9/10/2021)

In addition to understanding what influences bitcoin price on a daily basis, we also need to understand how gold's price is affected. Once we know what has the power to make both forms of currency's prices fluctuate, we will be able to start modeling. Upon researching how gold's price is affected in the current era, we have found that what affects the price of gold the most is supply and demand and the value of the United States (U.S.) dollar.

Supply and Demand

Gold is used in many goods bought and sold throughout the entire world. Therefore, it is in high demand, which is why gold has always been so valuable. From jewelry to electronics and medical devices, everyone has a use for gold. Gold is not just in high demand by the ordinary consumer, but gold is also seen as a universal currency. Therefore, many nations have reserves that store gold in addition to their paper currency. Overall, as gold is needed for the production of medical devices and electronics, and demanded for jewelry, the price of gold is driven upwards.

In addition, gold mining also affects its price. Low supply and production will yield high prices of gold. Also, as more gold is mined and therefore, becoming harder to find. Miners will have to drill deeper into the earth to find quality reserves. With the need to drill deeper, comes increased costs of production, and therefore, increased gold prices. [4]

Value of the U.S. Dollar

It has been seen that the value of gold and the value of the United States dollar have an inversely proportional relationship. Therefore, when the value of the dollar is lower, the price of gold rises. On the contrary, when the value of the dollar is higher, the price of gold decreases. This is why gold can be looked at as a guard against inflation since it has the opposite effect. [4]

1.3 Overview of Trading Strategies

When trading in financial markets, knowing the different types of trading strategies is imperative. There are three main steps to most trading strategies: planning, placing trades, and executing trades [7]. At each step in the process, quantitative assessments are used to critique the strategy based on changes in the market. For our model, we specifically researched daily trading strategies to find the best fit for trading bitcoin and gold on a day-to-day basis. Below is an analysis of the different daily strategies we researched. [5]

Momentum Trading

Momentum trading is a strategy in which an investor trades into one of about 0.20% of stocks that fit the qualifications of a momentum trade. Momentum stocks have the potential to move twenty or even thirty percent. The qualifications for a momentum stock are [3]:

- The stock must be moving.
- The stock must have less than one hundred million outstanding shares.
- The stock must appear strong on the daily charts by having no nearby resistance and being above the moving averages.
- The stock must have a high relative volume of at least twice above the average.
- There must be a fundamental catalyst that caused the increase in value.
    - Example: FDA announcement, a drug company discovering a new treatment, news that a small company has been bought out by a large firm, etc.

Momentum trading comes with many advantages and disadvantages. One of the advantages is significant profits can be seen on a daily or weekly basis. Another advantage is momentum trading is relatively simple compared to other trading strategies. While other strategies require a long-term understanding of the many factors of investing, momentum trading focuses through a

single lens on the technical analysis of charts. On the other hand, a disadvantage of momentum trading is it involves a lot of buying and selling which leaves room for mistakes. In addition, momentum trading trends can be thrown off in an instant by a fundamental development or a press release. [9]

Scalping Strategy

The scalping strategy values small trades over large trades on the principle that small trades (sometimes hundreds) will add up to a large sum of money at the end of the day. With scalping, often multiple trades are made within seconds, if not, stocks are only held for minutes. Scalping is for confident and focused traders as decisions need to be made fast — becoming distracted even for a second may cause one to miss an integral trend in the market. The main rules for scalping are [11]:

- Trade high demand stocks
- Buy when the price of the stock moves above a resistance area and one sees an instant move up after entry
- Sell immediately when there is no move up in a stock's price
- Sell immediately when one gains a small profit
- Take 3-5 trades until the daily goal is met

Some advantages to scalping are it is low risk and offers many trading opportunities each day. However, due to transaction costs, it is hard for a scalper to make money. Although scalping reduces vulnerability in the stock market, it is a long, tedious game of small wins.

Pullback Trading Strategy

A day trader who uses the pullback trading strategy uses technical charts to analyze a stock's trend. If the established trend is upward, the trader waits for a price decline, or pullback then buys into the stock. The risk to this is, what one might think is a pullback is in fact a reversal, and the stock price continues to decrease. Pullback trading is not for the impatient. A pullback trader must pay attention and wait patiently for the pullback. [1]

Breakout Trading

Breakout trading involves identifying current price trend patterns, support levels, resistance levels, and creating a plan for possible buy-in and sell-out points. A breakout is when the stock price exceeds a resistance level or falls below a support level. Someone who utilizes breakout trading finds stocks that have strong support and resistance levels. [8] Breakout traders watch these stocks very carefully, wait for the stock price to move, and then buy in near the end of the trading day. An advantage of breakout trading is there is potential for quick gains since one buys at the bottom of the range. On the other hand, a daily breakout is not guaranteed. Some breakouts may take days to yield returns. [2]

Fading Strategy

Fading is essentially the opposite of momentum trading. This is a high-risk strategy in which seasoned investors trade against the market trends. An investor who utilizes fading buys when stocks are falling and sells when they are rising. Investors who use fading also often use micro-

lot trading. Micro-lot trading is when investors split trading into small lots and purchase stocks at many different price levels. Faded trades have two ways of entry [6]:

1. Regular: When the trade is distributed into equal portions across a region.
2. Pyramid: When the trade is weighted heavily at the end of each region.

2 Assumptions

We used the following assumptions in selecting our prediction model and trading strategy:

1. Trades settle instantly.
2. There is no direct way to swap bitcoin for gold or gold for bitcoin. Combined with the assumption (1), we can indirectly perform either swap by paying a fee of 2.98%.
3. Markets are open on each day for which the provided datasets contain price information. We ignore N/A rows from those datasets.
4. There are no tax considerations, except those possibly included in the trading fees. Dropping this assumption, it may be strategic to hold an asset for an entire year to benefit from the lower taxation of long-term capital gains.
5. The client prefers that the final portfolio be distributed for short-term success. If the client would prefer the final portfolio to consist entirely of cash, we may be more cautious in buying assets near the end of the period.

3 Model Description

To present the best trading strategy, we constructed a model that not only gives us an accurate prediction of the future prices of bitcoin and gold but also takes asset balance and risks into account.

3.1 Prediction Model

Autoregressive Integrated Moving Average (ARIMA) Models

To predict prices for bitcoin and gold, we simulated our predictions with Autoregressive Integrated Moving Average (ARIMA) Models. The formula for ARIMA(p, d, q) has the structure below:

$$\hat{y}_t = \mu + \sum_{i=1}^{p} \alpha_i y_{t-i} + \sum_{j=1}^{q} \beta_j e_{t-j} + e_t,$$

The parameters we are interested in optimizing are defined as follows:

- p: indicates the number of autoregressive terms
- d: indicates the difference needed to make the series stationary
- q: indicates the number of moving average terms (lags of the forecast errors)

A log transformation of the time series can be helpful when differencing. The time series appears stationary regarding mean but not regarding variance. [12]

$$\Delta \ln(y_t) = \ln(y_t) - \ln(y_{t-1})$$

Parameter Selections

To optimize the parameters of the ARIMA models, we first needed to select potential candidates based on Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC). Then, we had to evaluate these candidates based on Mean Average Percentage Error (MAPE).
We evaluated our top six ARIMA models using Walk Forward Validation. In this testing paradigm, we evaluated each candidate model at a time t using the given data through time t – 1. [12] While this form of validation is computationally expensive, the optimizations provided by the R package `astsa` in R allowed us to obtain a Mean Average Percentage Error (MAPE). According to potential model candidates' MAPE, we decided to pick the ARIMA(1, 1, 1) model for bitcoin prediction and the ARIMA(4, 1, 0) model for gold prediction.

Bitcoin Prediction Model Candidates		
Model	Strengths	MAPE
ARIMA(0, 1, 0)	• Low BIC • Can calculate by hand	0.306%
ARIMA(1, 1, 1)	• Low AIC • Low number of parameters	0.303%
ARIMA(5, 0, 2)	• Lowest AIC	17.80%
AIC: Akaike Information Criterion BIC: Bayesian Information Criterion MAPE: Mean Absolute Percentage Error ARIMA: Autoregressive Integrated Moving Average		

Figure 3: Candidates for the Bitcoin Prediction Model and their strengths & MAPEs

Gold Prediction Model Candidates		
Model	Strengths	MAPE
ARIMA(2, 1, 2)	• Low AIC	0.331%
ARIMA(4, 1, 0)	• Low AIC	0.248%
AIC: Akaike Information Criterion MAPE: Mean Absolute Percentage Error ARIMA: Autoregressive Integrated Moving Average		

Figure 4: Candidates for the Gold Prediction Model and their strengths & MAPEs

Using MAPE to evaluate model adequacy

For our trading strategy, we care more about the direction in which prices will move than the magnitude. This makes traditional accuracy metrics, such as MAPE, imperfect candidates for model evaluation. For example, on 29 April 2017, the given price of Bitcoin rose from $1331.29 to $1334.98. Suppose a model predicted that the price would fall 3% to $1291.35. Then that model achieves a respectable Absolute Percentage Error (APE) of 3%, even though it would mislead us into selling our Bitcoin. Conversely, on 1 May 2017, Bitcoin shot up from $1333 to $1417.17. If our model predicted an increase to $1780 (the price on 15 May 2017), then our

model would suffer an APE of 3.35%, despite correctly leading us to buy Bitcoin for a massive profit.

While we considered several alternatives to MAPE, none of them resolved the fallacies of MAPE without introducing new issues.

- Differencing data before evaluating MAPE would encourage directional sensitivity but would overly weight models' performance on days without much price change.
- Switching to a categorical approach would reward models that are imprudently insensitive to fees. For example, consider a classification model, such as k-nearest neighbors, that predicts merely whether the price will go up or down. This model may perform well under a categorical metric but would not be useful in determining a trading strategy, as we would not know whether the upcoming price activity merits paying the trading fee.
- The Mean Squared Error (MSE) falls short in that it would give undue consideration to later days when assets (particularly Bitcoin) are worth more. For instance,

Ultimately, MAPE appears to be the industry standard [12] for evaluating time-series performance, so despite its flaws, we use it for Walk Forward Validation of our six ARIMA models.

3.2 Trading Strategy Model

Price predictions alone are not sufficient to dictate when to buy and when to sell. We consider several other factors, including balance of terms, risk management, the balance of assets, and fee sensitivity in determining our strategy.

Balance of Terms

The short term bears the most reliable predictions and provides the greatest overall opportunity for profit, as the profits from one day may be compounded by the profits from the next. However, trading exclusively on a daily line of reasoning leads one to be overly sensitive to trading fees, missing out on small (< fee) but consistent day-to-day gains over a long period of time.

		Daily Prediction			
Monthly Prediction	Trend	↑	↗	↘	↓
	↑	Buy	Buy	Hold	Sell*
	↗	Buy	Hold	Hold	Sell*
	↘	Buy*	Hold	Hold	Sell
	↓	Buy*	Hold	Sell	Sell

*Excluding Fridays for gold; in this case, it would be a 3-day prediction.

Figure 2: A table showing monthly vs. daily trend predictions and whether we would buy, sell, or hold at the moment both predictions happen simultaneously. A straight arrow pointing up indicates the prices of bitcoin and gold have increased and are worth more than the transaction fee. A slanted arrow pointing up and to the right indicates the prices of bitcoin and gold have increased, however, are less than the transaction fee. A slanted arrow pointing down and to the right indicates the prices of bitcoin and gold have decreased, however, not as much as the transaction fees. Lastly, a straight-arrow pointing down indicates the prices of bitcoin & gold have decreased more than the transaction fees.

Risk management

Our consideration of the balance of terms determines what action to take, but not how much of that action. If Figure 2 tells us that we should buy Bitcoin, how much should we buy? Assuming liquidity (which is clear for gold and increasingly true for Bitcoin), our expected gain from the transaction is proportional to how much we buy. However, if we shift 100% of our portfolio to a particular asset, then we risk an extreme loss. For example, if we shifted our entire portfolio to Bitcoin on 13 March 2020, then we would lose $\frac{7936.65-4830.21}{7936.65} \cdot 100\% = 39.1\%$ of it on that day alone. Such a meteoric single-day loss may greatly upset investors and even lead to legal proceedings.

To combat such risks, we divide our portfolio among a family of algorithmic agents, each of which reaches a decision based on its unique prediction interval. For example, one agent determines an 80% prediction interval around each prediction, i.e., the agent finds that the likelihood of its interval capturing the coming day's price is 80%. If the agent's interval is entirely greater than the current price *plus the fee*, then the agent buys the asset with its portion of the portfolio. Otherwise, if the interval entirely exceeds the current price (not *plus the fee*), then the agent shifts its interval to the monthly prediction; if the interval then exceeds the current price *plus the fee*, then it purchases the asset. Similar rules govern the sale of assets, detailed in the next subsection. The appendix details the exact distribution of agents and their prediction levels.

Balance of Assets

Bitcoin and gold have little correlation, so diversification between the two achieves a less volatile portfolio than even the average volatility of the two. While splitting our portfolio between the two mitigates overexposure to either asset, it also decreases our expected gains compared to putting our entire portfolio into the asset favored by our prediction model. To compromise the two approaches, we allow each of our algorithmic agents to make their own daily choice between Bitcoin, gold, and cash. While all agents will purchase either asset from time to time, some agents are biased to one asset over the other. Specifically, agents' risk tolerance for Bitcoin is uncorrelated with agents' risk tolerance for gold, so an agent requiring the strongest prediction to buy Bitcoin may buy gold the moment its predicted price exceeds its current price plus the fee.

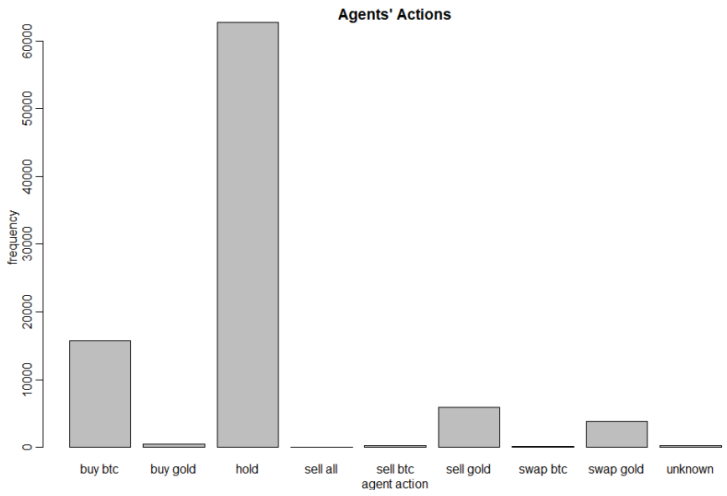
In real-world trading, it is often possible to trade one asset directly for another, saving on transaction fees compared to going through cash. Binance.us, the leading US cryptocurrency exchange, allows direct Bitcoin/tokenized gold (BTC/PAXG) trading for a prepaid fee of just 0.075%, or a postpaid fee of 0.1%. For our solution, however, we will assume that a direct

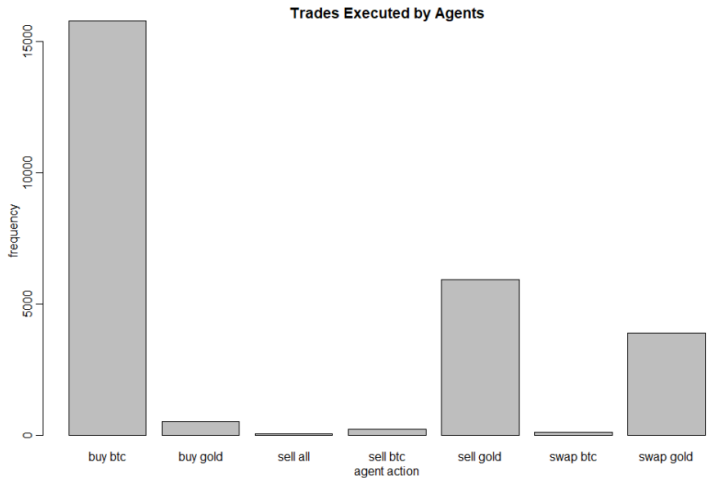
Bitcoin/gold market is not available. For an agent to swap Bitcoin for gold, it must first sell Bitcoin for cash, then buy gold with the cash, paying a total fee of $0.02 + (0.01 \cdot 0.98) = 2.98\%$. Due to this high fee, agents must see extraordinary evidence to swap one asset for another: The predicted gains from the swap must exceed the combined fee by agents' *combined* risk tolerance. For example, an agent using width 4 (conservative) intervals for Bitcoin and width 1 (risky) intervals for gold would use width 5 (very conservative) intervals when considering swaps.

4 Results and Discussions

4.1 Trading Actions

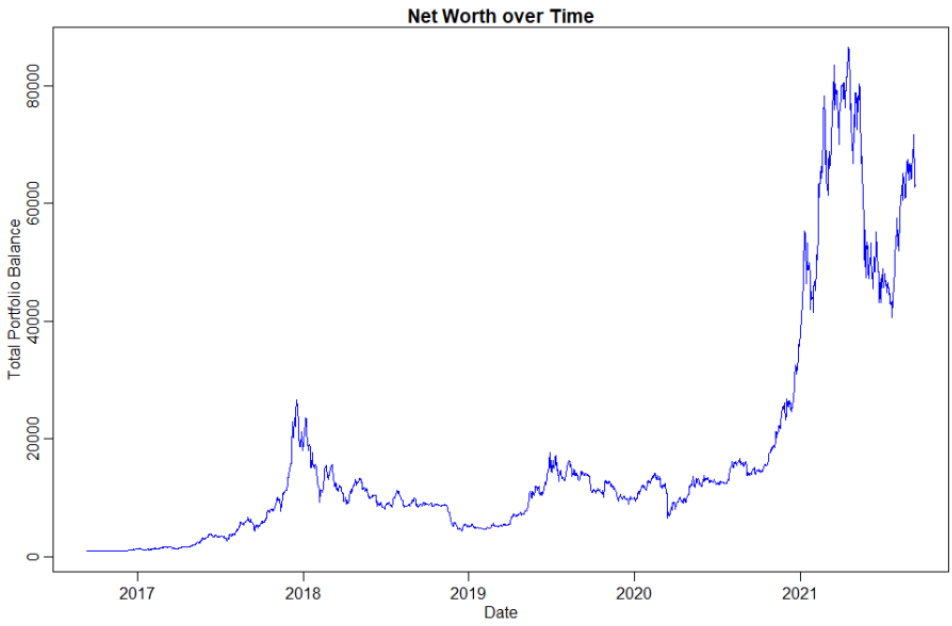
Below is a summary of the potential actions and their frequencies of being chosen by our trading algorithm. Using our model to determine agents' actions, we observed that our strategy suggests the action "hold" more significantly than any other actions. Based on the real value of bitcoin over the given time period, we understand that choosing to hold is the best strategy to maximize the net worth. Among all suggested trading actions, buying bitcoin is considered the top choice during the given trading period. Notice that our strategy suggests buying bitcoin much more frequently than buying gold. Interestingly, our strategy suggests selling gold with the highest frequency, which means that profit-wise, we are most likely to not hold gold while holding bitcoin.





4.2 Net Worth

Our risk-aware strategy paid off, building a starting portfolio of $1000 up to a final portfolio of net worth $63,147 while never falling below $929. See the plot of net worth over time below, our net worth fluctuates throughout the time, but it is heading towards a promising direction up to 9/10/2021. If we continue to implement our trading algorithm, we expect that the net worth will continue to rise. We confirmed that the trading algorithm's suggestion is effective – as we continue to hold our bitcoins, the net worth would along with the market.



5 Sensitivity to Transaction Costs

We have tested our trading algorithm on different values of the transaction cost. The table below summarizes the final net worth under different transaction costs. Our trading algorithm works the best under the standard fees given, while it performs closely well when fees that are doubled or halved. However, when the transaction cost is set to near 0 based on the Binance.us from a leading US cryptocurrency exchange, we see that our final net worth is cut in half. When the transaction cost is close to 0, it perhaps signals to our algorithm that it is less risky so conducting more transactions is encouraged. However, since we know the most frequent action our algorithm recommends is to hold, a small transaction cost can break this balance. Hence, we can conclude that our algorithm is sensitive to dramatic changes (0.075%, 0.075%) in transaction cost and performs relatively the same when the fees are around the standard range (2%, 1%).

Sensitivity to Transaction Costs		
Transaction Fee for Bitcoin (%)	Transaction Fee for Gold (%)	Net Worth ($)
0.075%	0.075%	$33,137.48
1%	0.5%	$55,595.96
2%	1%	$63,147.37
4%	2%	$59,142.43

6 Conclusion

To best make predictions on whether to buy, hold, or sell bitcoin daily we understand that the market price and people's demand mainly influence the price of bitcoin. We found that gold's maturity and bitcoin's immaturity translated to their market behavior. One of the most important steps of trading model design is to find the model that excels in prediction. Using ARIMA model to predict time series data allows our chosen trading strategy to consider both daily forecasts and 30-day forecasts. Also, the ARIMA model can provide standard errors rather than just the predictions themselves, which enables us to calculate the prediction interval and determine trading actions.

In addition to prediction, we have also considered several other factors, including balance of terms, risk management, the balance of assets, and fee sensitivity, in determining our strategy. The results we get from our trading model are promising in net worth, as it suggested we should hold our bitcoins and sell the gold. Notice that the given transaction cost is relatively high compared to real-life scenarios, hence one limitation of our strategy is that it has difficulty in integrating into low transaction cost.

The model we developed was simplified by several assumptions, such as there are no tax considerations, we ignore N/A rows from days that market is closed, and trading settles instantly.

7 Memorandum

Date: February 19, 2022
To: Reputable Trader
From: Team # 2227952
Subject: Strategy, Model, & Results

As you know, the team members of team # 2227952 have been working hard to develop the most efficient daily trading strategy for you to profit in bitcoin and gold, starting with a $1,000 investment on 9/11/2016. The transactions costs of 1% and 2% for gold and bitcoin respectively were tough. However, we believe we have developed a great model and accompanying trading strategy to make you a considerable profit.

To predict the prices of bitcoin and gold, we suggest the ARIMA(1, 1, 1) and ARIMA(4, 1, 0) models, respectively. The ARIMA model with middle parameter d = 1 allows predictions to be sensitive to daily changes in price rather than daily price. After all, we are concerned with how much these assets will change each day, regardless of their starting price. Bitcoin is an immature and enigmatic asset, favoring the short-term memory of the ARIMA(1, 1, 1) model. On the other hand, gold is one of the market's most mature commodities, favoring the farther-seeing ARIMA(4, 1, 0) model, which dismisses moving average information to which the gold market has completely adjusted.

Additionally, we recommend using the log scale when for prices to adjust for the exponential behavior of bitcoin price and to a lesser extent gold price. Furthermore, we advise adding the number of days from today as a covariate to each model to mitigate the non-stationarity caused by inflation.

Going all-in on a specific level of risk tolerance would overexpose results to the risk-benefit trade-off. We suggest instead dividing the portfolio among 49 algorithmic agents evenly each day. Each algorithmic agent takes a risk avoidance level L from 0 to 6 for each bitcoin and gold, for a total of 49 agents. Each agent then only executes a trade predicted to be profitable if the prediction is at least L standard deviations above the current price plus (buy) or minus (sell) the fee.

Our algorithm recommends actions including buy, sell, and hold. Also, we consider the swap as one of our trading strategies. In real-world trading, it is often possible to trade one asset directly for another, saving on transaction fees compared to going through cash. In our case, the transaction cost is relatively high, compared to the current leading US cryptocurrencies trading rate. Due to this high fee, agents must see extraordinary evidence to swap one asset for another.

Using our model to determine agents' actions, we are suggesting traders hold more than other actions. If buy/sell is needed, we suggest buying bitcoin and selling gold. Based on our risk-aware strategy, we are pleased to see that our starting portfolio of $1000 went up to a final portfolio of net worth $63,147 while never falling below $929.

In addition, our algorithm performs consistently by doubling or halving the transaction cost, while a big change in transaction cost might mislead us to conduct more trading than holding current assets. Therefore, it is recommended to be cautious about whether there is a significant change in the transaction cost while using this algorithm to determine the trading action.

Sincerely,

Team # 2227952

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9 Appendices

9.1 Appendix A: Agent Specifications

For our purposes, an agent is an automaton that, each day, takes an equal portion of the portfolio, executes any trades it deems prudent, and returns the resulting balances to the portfolio. For each m and n in S = {0, 1, 2, 3, 4, 5, 6}, we construct an agent with bitcoin risk parameter btc_zcrit and gold risk parameter gold_zcrit. The parameter btc_zcrit is the number of ARIMA standard errors above the current bitcoin price *plus the fee* that an ARIMA prediction must fall to lead the agent to buy the asset. A similar approach is used for buying gold or selling either asset. For swaps between bitcoin and gold, the agent uses the sum of btc_zcrit and gold_zcrit. Note that S is a hyperparameter tuned to nearly optimize overall profit while maintaining holistic risk management.

9.2 Appendix B:

(Partial) Trading Strategy Code

```
action_log = rep("unknown", nrow(bitcoin) * sqrt_agents * sqrt_agents)
action_log_dex = 1
portfolio_cgb = c(1000, 0, 0)
bitcoin_balance_tracker <- gold_balance_tracker <- cash_balance_tracker <-
rep(0, length(bitcoin) + 1)
balance_tracker_dex = 1
btc_index = 0
gold_index = 0
skip_days = 5
for (day in days) {
  bitcoin_balance_tracker[balance_tracker_dex] = portfolio_cgb[3]
  gold_balance_tracker[balance_tracker_dex] = portfolio_cgb[2]
  cash_balance_tracker[balance_tracker_dex] = portfolio_cgb[1]
  balance_tracker_dex = balance_tracker_dex + 1
  #update portfolio
  if (skip_days == 0) {
    if (day %in% gold$Date) {
      portfolio_cgb[2] = portfolio_cgb[2] * exp(gold$logVal[gold_index + 1] -
gold$logVal[gold_index])
    }
    portfolio_cgb[3] = portfolio_cgb[3] * exp(bitcoin$logVal[btc_index + 1] -
bitcoin$logVal[btc_index])
  }

  #make trades
  btc_index = btc_index + 1
  portfolio_split <- portfolio_split_original <- portfolio_cgb / (sqrt_agents
** 2)
  portfolio_cgb_skip = portfolio_cgb
  portfolio_cgb = rep(0, 3)
  if (day %in% gold$Date) {
    gold_index = gold_index + 1
    if (skip_days > 0) {
      skip_days = skip_days - 1
```

```
      portfolio_cgb = portfolio_cgb_skip
      next
    }
    for (agent_row in agents) {
      for (agent in agent_row) {
        # bitcoin$upper_pred = bitcoin$daily_pred + agent$btc_zcrit *
bitcoin$daily_sd
        # bitcoin$lower_pred = bitcoin$daily_pred - agent$btc_zcrit *
bitcoin$daily_sd
        # gold$upper_pred = gold$daily_pred + agent$gold_zcrit * gold$daily_sd
        # gold$lower_pred = gold$daily_pred - agent$gold_zcrit * gold$daily_sd
        action = "hold" # hold, buy btc, buy gold, sell btc, sell gold, sell
all, swap btc, swap gold
        if (z_buy_btc[btc_index] > agent$btc_zcrit ||
            (z_buy_btc[btc_index] > -z_sell_btc[btc_index] &&
             z_buy_btc_monthly[btc_index] > agent$btc_zcrit)) {
          action = "buy btc"
        }
        else if (z_sell_btc[btc_index] < -agent$btc_zcrit ||
                 (z_buy_btc[btc_index] < -z_sell_btc[btc_index] &&
                  z_sell_btc_monthly[btc_index] < -agent$btc_zcrit)) {
          action = "sell btc"
        }
        if (z_buy_gold[gold_index] > agent$gold_zcrit ||
            (z_buy_gold[gold_index] > -z_sell_gold[gold_index] &&
             z_buy_gold_monthly[gold_index] > agent$gold_zcrit)) {
          if (action != "buy btc" || z_buy_gold[gold_index] >
z_buy_btc[btc_index]) {
            if (action == "sell btc") {
              action = "swap btc"
            }
            else {
              action = "buy gold"
            }
          }
        }
        else if (z_sell_gold[gold_index] < -agent$gold_zcrit ||
                 (z_buy_gold[gold_index] < -z_sell_gold[gold_index] &&
                  z_buy_gold_monthly[gold_index] < -agent$gold_zcrit)) {
          if (action == "sell btc") {
            action = "sell all"
          }
          else if (action == "buy btc") {
            action = "swap gold"
          }
          else {
            action = "sell gold"
          }
        }
        if (action == "buy btc" && portfolio_split[2] > 0) {
          if (z_buy_btc[btc_index] > z_sell_gold[gold_index]) {
            action = "swap gold"
          }
        }
        else if (action == "buy gold" && portfolio_split[3] > 0) {
          if (z_buy_gold[gold_index] > z_sell_btc[btc_index]) {
```

```
            action = "swap btc"
          }
        }

        action_log[action_log_dex] = action
        action_log_dex = action_log_dex + 1
        if (action == "buy btc") {
          portfolio_split[3] = portfolio_split[3] + (1 - fee_btc) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else if (action == "sell btc") {
          portfolio_split[1] = portfolio_split[1] + (1 - fee_btc) *
portfolio_split[3]
          portfolio_split[3] = 0
        }
        else if (action == "buy gold") {
          portfolio_split[2] = portfolio_split[2] + (1 - fee_gold) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else if (action == "sell gold") {
          portfolio_split[1] = portfolio_split[1] + (1 - fee_gold) *
portfolio_split[2]
          portfolio_split[2] = 0
        }
        else if (action == "sell all") {
          portfolio_split[1] = portfolio_split[1] + (1 - fee_gold) *
portfolio_split[2] + (1 - fee_btc) * portfolio_split[3]
          portfolio_split[2] = 0
          portfolio_split[3] = 0
        }
        else if (action == "swap btc") {
          portfolio_split[2] = portfolio_split[2] + (1 - fee_btc) * (1 -
fee_gold) * portfolio_split[3]
          portfolio_split[3] = 0
          #implies that we should also buy gold with cash
          portfolio_split[2] = portfolio_split[2] + (1 - fee_gold) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else {
          stopifnot(action == "hold")
        }
        portfolio_cgb = portfolio_cgb + portfolio_split
        portfolio_split = portfolio_split_original
      }
    }
```

```
  }
  else {
    if (skip_days > 0) {
      skip_days = skip_days - 1
      portfolio_cgb = portfolio_cgb_skip
      next
    }
    for (agent_row in agents) {
      for (agent in agent_row) {
        action = "hold"
        if (z_buy_btc[btc_index] > agent$btc_zcrit) {
          action = "buy btc"
        }
        else if (z_sell_btc[btc_index] < -agent$btc_zcrit) {
          action = "sell btc"
        }

        action_log[action_log_dex] = action
        action_log_dex = action_log_dex + 1
        if (action == "buy btc") {
          portfolio_split[3] = portfolio_split[3] + (1 - fee_btc) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else if (action == "sell btc") {
          portfolio_split[1] = portfolio_split[1] + (1 - fee_btc) *
portfolio_split[3]
          portfolio_split[3] = 0
        }
        else if (action == "buy gold") {
          portfolio_split[2] = portfolio_split[2] + (1 - fee_gold) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else if (action == "sell gold") {
          portfolio_split[1] = portfolio_split[1] + (1 - fee_gold) *
portfolio_split[2]
          portfolio_split[2] = 0
        }
        else if (action == "sell all") {
          portfolio_split[2] = portfolio_split[2] + (1 - fee_btc) * (1 -
fee_gold) * portfolio_split[3]
          portfolio_split[3] = 0
          #implies that we should also buy gold with cash
          portfolio_split[2] = portfolio_split[2] + (1 - fee_gold) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else if (action == "swap gold") {
```

```
          portfolio_split[3] = portfolio_split[3] + (1 - fee_btc) * (1 -
fee_gold) * portfolio_split[2]
          portfolio_split[2] = 0
          portfolio_split[3] = portfolio_split[3] + (1 - fee_btc) *
portfolio_split[1]
          portfolio_split[1] = 0
        }
        else {
          stopifnot(action == "hold")
        }
        portfolio_cgb = portfolio_cgb + portfolio_split
        portfolio_split = portfolio_split_original
      }
    }
  }

}
```