Triangular Arbitrage on Binance with Real Data Stream

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1. Abstract

This project endeavors to unveil an exquisite and refined implementation of the prevailing triangular arbitrage strategy. Meticulous testing shall ensue, encompassing both software and hardware domains. The commencement of actual trading activities shall be contingent upon the demonstrable profitability of this arbitrage approach. Triangular arbitrage will be implemented using both sequential and concurrent methodologies. Sequential arbitrage involves the execution of three trades in a linear fashion, where each trade is initiated after the completion of the previous one. On the other hand, concurrent arbitrage involves the simultaneous initiation of three trades, allowing them to be executed asynchronously. The algorithm of Trading Gate would be implemented with JavaScript, Node.JS, Web Socket, and the Binance API. With triggered trading signals, arbitrage results within predefined time intervals would be diligently processed and seamlessly integrated into a Google Sheet via Google APIs. An adaptable and versatile Generic Backend solution is meticulously crafted to seamlessly process incoming requests from the Trading Gate. Its design ensures compatibility with any front-end system, offering a sophisticated and elegant solution for streamlined integration. About the software component, the optimization efforts will focus on enhancing the search algorithms with the explicit reduction of time complexity. From a hardware standpoint, an exhaustive analysis will be conducted to rigorous scrutiny. This meticulous evaluation will unveil and meticulously assess the discernible disparities in their respective performances. Consequently, the analysis would be undertaken to scrutinize the principal impediments obstructing profitability in triangular arbitrage.

2. Objective

Arbitrage, with its extensive historical lineage, stands as a testament to human wisdom in the realm of trading. Throughout the annals of economic development, astute individuals recognized the potential for profit by exploiting price differentials across markets. From the ancient Silk Road to the bustling trading floors of modern exchanges, arbitrage has persisted as a cornerstone of commerce. Its enduring presence underscores the shrewdness and acumen of human traders who devised strategies to capitalize on market inefficiencies [1]. Through meticulous analysis,

discerning observation, and nimble execution, arbitrageurs have unlocked hidden opportunities and reaped substantial rewards. The practice of arbitrage embodies the human capacity to discern patterns, exploit informational advantages, and navigate complex financial ecosystems. As a testament to human wisdom, arbitrage continues to thrive as a pillar of financial ingenuity, propelling economies forward and enriching those who possess the sagacity to seize their potential.

3. Introduction

3.1. Financial Assets

3.1.1. Stocks

A stock, recognized as equity, embodies a security that symbolizes fractional ownership in the issuing corporation. These distinct units, referred to as "shares," bestow upon their possessor a commensurate claim to a portion of the corporation's assets and profits, proportional to the magnitude of their stock holdings [2].

Stocks (Equities)

1. Apple Inc. - AAPL
2. Microsoft Corporation - MSFT
3. Amazon.com Inc. - AMZN
4. Alphabet Inc. - GOOGL
5. Facebook Inc. - FB

3.1.2. Bonds

A bond, esteemed as a fixed-income instrument, epitomizes a loan extended by an investor to a borrower, often encompassing corporate or governmental entities. Conceptually akin to an I.O.U., a bond encompasses the intricate particulars of the loan arrangement and its corresponding payments. Bonds serve as a pivotal mechanism for companies, municipalities, states, and sovereign governments to secure requisite funding for a myriad of projects and operational endeavors [3]. Those who possess bonds assume the role of debtholders or creditors, holding a vested interest in the issuer's financial obligations.

Bonds

1. United States Treasury Bonds
2. Japanese Government Bonds
3. German Government Bonds
4. United Kingdom Government Bonds
5. French Government Bonds

3.1.3. Currencies

Currency, revered as a paramount medium of exchange, orchestrates the seamless flow of goods and services. In essence, it embodies the essence of monetary value, manifesting as tangible paper and coins, conventionally bestowed by a governing body and ubiquitously acknowledged at its nominal worth, serving as an expedient method of financial settlement [4].

Currencies (Forex)

1. United States Dollar - USD
2. Euro - EUR
3. Japanese Yen - JPY
4. British Pound - GBP
5. Swiss Franc - CHF

3.1.4. Commodities

A commodity, a fundamental component of commerce, epitomizes a foundational good that exhibits interchangeability with other goods of a similar nature [5]. Primarily employed as inputs in the production of diverse goods and services, commodities exemplify raw materials harnessed in the fabrication of finished products. In contrast, a product signifies the consummated artifact marketed to discerning consumers.

Commodities

1. Gold - XAU
2. Crude Oil - CL
3. Silver - XAG
4. Copper - HG
5. Natural Gas - NG

3.1.5. Derivatives

It encapsulates a distinctive breed of financial agreement wherein the valuation is contingent upon an underlying asset, a collection of assets, or a benchmark [6]. Derivatives materialize through contractual arrangements forged between two or more parties, who are granted the capacity to engage in trade either through established exchanges or via over-the-counter (OTC) channels.

Derivatives

1. Interest Rate Swaps
2. Options Contracts
3. Futures Contracts
4. Credit Default Swaps (CDS)
5. Equity Swaps

3.1.6. Exchange-Traded Funds (ETFs)

An exchange-traded fund (ETF) represents an exemplar of a pooled investment security, sharing notable similarities with mutual funds. Traditionally, ETFs are designed to replicate the performance of specific indices, sectors, commodities, or other assets [7]. Distinguishing them from mutual funds, ETFs can be effortlessly bought or sold on stock exchanges, akin to regular stocks. The versatility of ETFs allows for their structuring to track an array of entities, ranging from the value of a singular commodity to an extensive and diversified assortment of securities. Moreover, ETFs can even be tailored to mirror distinct investment strategies, further exemplifying their adaptability and appeal.

Exchange-Traded Funds (ETFs)

1. SPDR S&P 500 ETF Trust - SPY
2. iShares MSCI ACWI ETF - ACWI
3. iShares Russell 2000 ETF - IWM
4. Invesco QQQ Trust - QQQ
5. iShares Core S&P 500 ETF - IVV

3.1.7. Index Funds

An index fund, whether in the form of a mutual fund or an exchange-traded fund (ETF), is meticulously composed to align with or mirror the constituents of a specific financial market index, such as the renowned Standard & Poor's 500 Index (S&P 500) [8]. Regarded as a vehicle for securing broad market exposure, index mutual funds offer the advantages of cost-efficient operations and minimal portfolio turnover. Remarkably resilient, these funds steadfastly adhere to their benchmark index regardless of prevailing market conditions.

Index Funds

1. Vanguard Total Stock Market Index Fund - VTSAX
2. Fidelity 500 Index Fund - FXAIX
3. Schwab Total Stock Market Index Fund - SWTSX
4. Vanguard 500 Index Fund - VFIAX
5. iShares Russell 2000 ETF - IWM

3.1.8. Cryptocurrencies

A cryptocurrency represents a form of currency existing in a digital or virtual realm, fortified by cryptography to render counterfeiting or double-spending virtually insurmountable [9]. The majority of cryptocurrencies operate within decentralized networks, leveraging the prowess of blockchain technology - a distributed ledger upheld by a diverse network of computers.

Cryptocurrencies

1. Bitcoin - BTC
2. Ethereum - ETH

3. Binance Coin - BNB
4. Cardano - ADA
5. XRP - XRP

3.2. Arbitrage Terminologies

3.2.1. Market Inefficiency

A condition where the prices of assets or securities do not accurately reflect their true values due to factors such as informational asymmetry, transaction costs, or market frictions [10]. It creates opportunities for profit through exploiting mispricings.

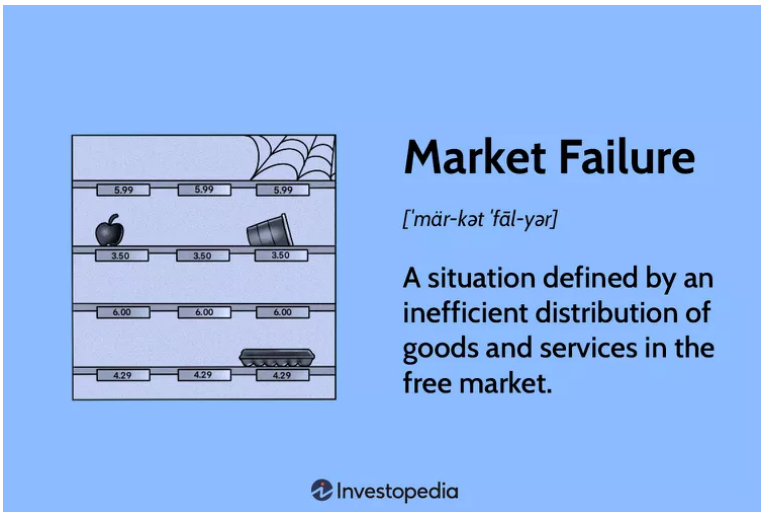

Figure 1: Market Failure from Investopedia

3.2.2. Convergence

The process by which prices or values of related assets or markets move closer together over time [11]. In arbitrage, convergence refers to the narrowing or elimination of price discrepancies between similar assets or markets.

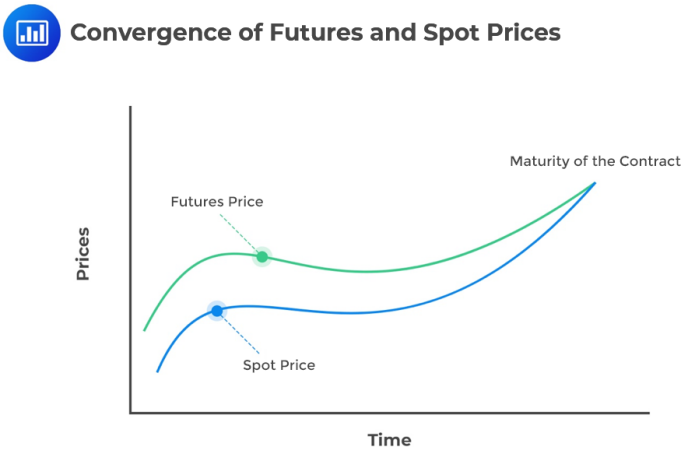

Figure 2: Convergence of Futures and Spot Prices from Analyst Prep

3.2.3. Risk-Free Profit

A profit earned without taking on any risk. In the context of arbitrage, risk-free profit refers to the opportunity to make a profit by exploiting price discrepancies without exposing oneself to market risks [12].

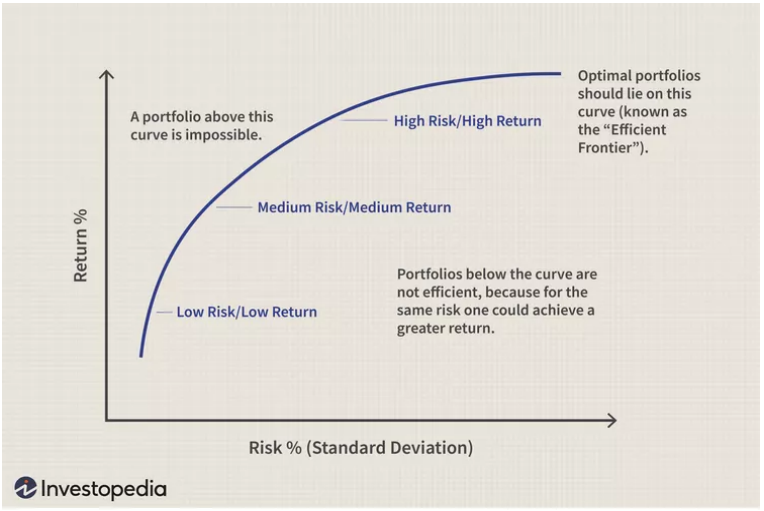

Figure 3: The T-Bill Base from Investopedia

3.2.4. Market Anomaly

An irregularity or deviation from the expected behavior of financial markets [13]. Market anomalies can arise due to various factors and may present opportunities for arbitrage or investment strategies.

3.2.5. Liquidity Imbalance

Order imbalance materializes as a circumstance arising from an extravagant surplus of buy or sell orders pertaining to a particular security on a trading exchange, impeding the harmonization of buyer and seller orders [14]. In instances where securities are under the purview of a market maker or specialist, shares may be summoned from a designated reserve to infuse liquidity, thereby temporarily alleviating the inventory burden engendered by the superfluity of orders.

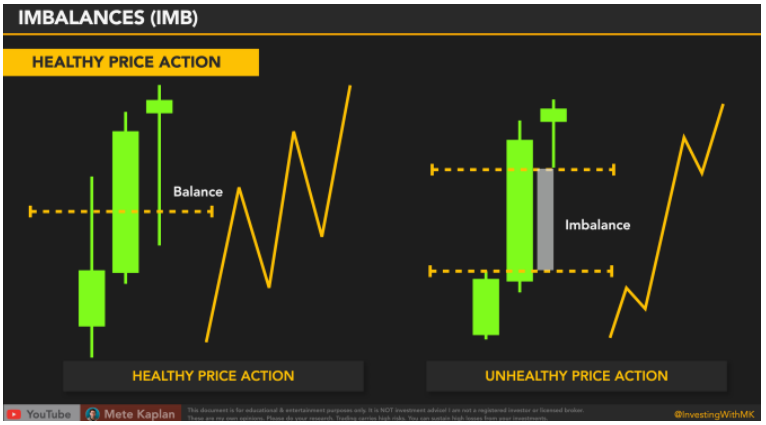

Figure 4: Balanced and Imbalanced Price Action from Mete Kaplan

3.2.6. Scalping

A short-term trading strategy that aims to profit from small price movements by quickly entering and exiting positions [15]. Scalpers typically execute numerous trades throughout the day to capture small profits repeatedly.

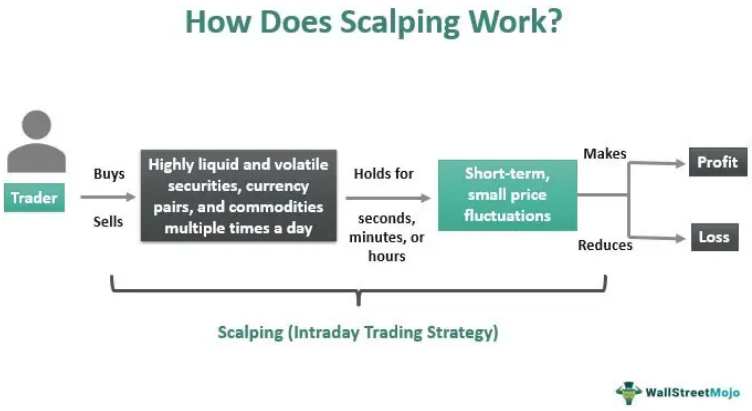

Figure 5: Scalping from WallStreetMojo

3.2.7. Slippage

The difference between the expected price of a trade and the actual executed price. Slippage can occur due to market volatility, liquidity imbalances, or delays in order execution, impacting the profitability of arbitrage trades [16].

3.2.8. Order Book

An order book provides a comprehensive view of the market's depth by displaying the number of shares being bid on or offered at various price levels. Additionally, it reveals the identities of market participants, although anonymity is sometimes maintained [17]. The presence of an order book not only aids traders in making informed decisions but also enhances market transparency by offering valuable trading insights.

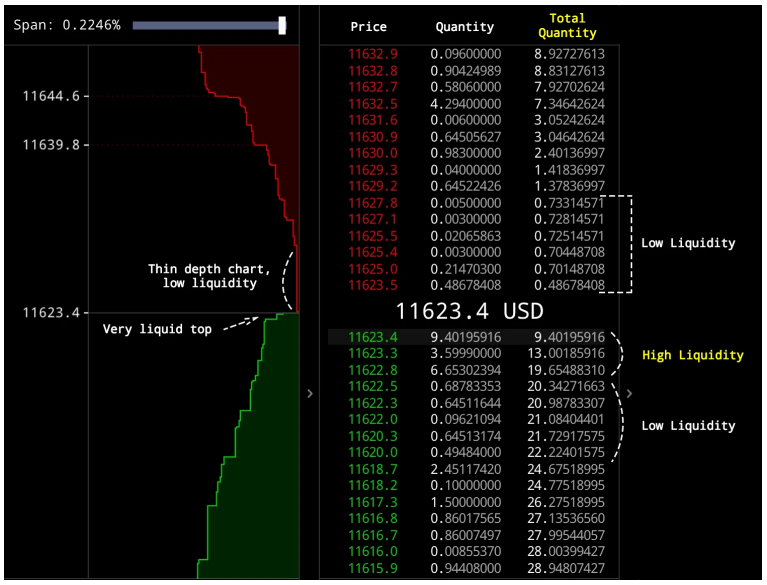

Figure 6: Order Book by BeInCrypto

3.3. Types of Arbitrage

3.3.1. Exchange Arbitrage

It refers to the practice of exploiting price discrepancies or inefficiencies between different exchanges or trading platforms. Traders engaging in exchange arbitrage take advantage of the temporary differences in prices for the same asset across different markets. By simultaneously buying at a lower price on one exchange and selling at a higher price on another, arbitrageurs seek to make risk-free profits from

the price differentials. The process typically involves quick and automated trading to capitalize on fleeting opportunities before market forces align the prices.

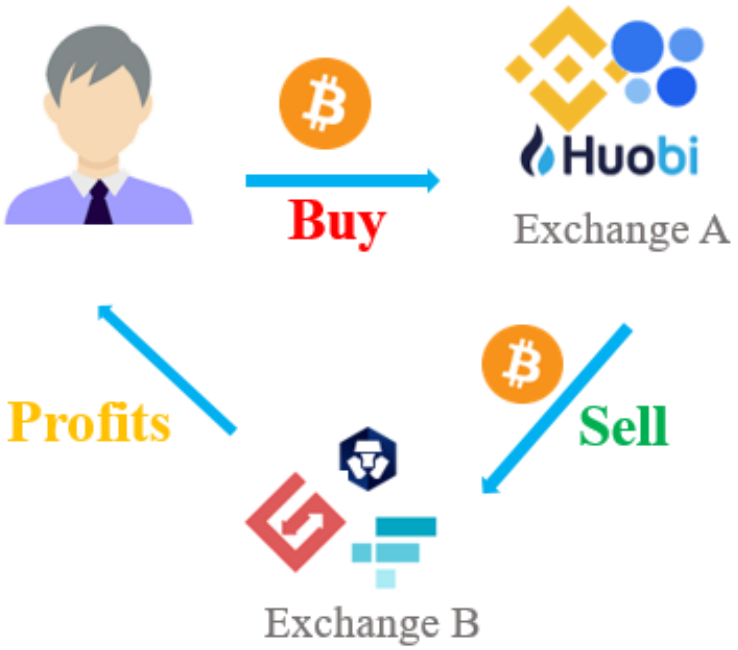

Figure 7: Exchange Arbitrage from Coin Carp

3.3.2. Triangular Arbitrage

It is a trading strategy utilized in the foreign exchange market to exploit price discrepancies among three different currency pairs. Traders engaging in triangular arbitrage aim to profit from inconsistencies in exchange rates by sequentially executing a series of currency conversions [18]. By carefully calculating the exchange rates and transaction costs involved, triangular arbitrage seeks to generate risk-free profits by taking advantage of temporary imbalances in the currency market. This strategy requires speed, precision, and automated trading systems to capitalize on fleeting arbitrage opportunities.

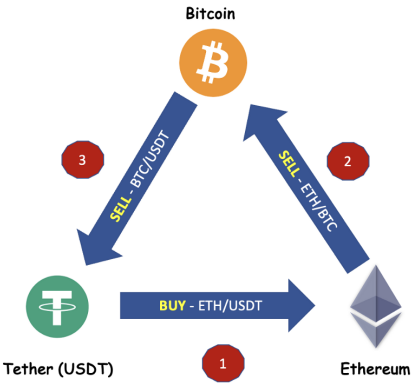

Figure 8: Triangular Arbitrage from GitHub

3.3.3. Statistical Arbitrage

It is a quantitative trading strategy that seeks to profit from statistical anomalies or patterns in the pricing relationships between financial instruments [19]. It involves using statistical models and analysis to identify deviations from expected price relationships and then executing trades to take advantage of these deviations. This strategy relies on the assumption that short-term price dislocations will eventually correct themselves, allowing traders to capture profits. Statistical arbitrage typically employs advanced algorithms and high-frequency trading techniques to swiftly identify and exploit these opportunities in the market.

Figure 9: Statistical Arbitrage from Investopedia

3.3.4. Futures Arbitrage

It is a trading strategy that aims to profit from price discrepancies between futures contracts and their underlying assets or related contracts. Traders engaging in

futures arbitrage simultaneously buy and sell futures contracts or related instruments to take advantage of differences in their prices [20]. This strategy relies on the principle of convergence, where the prices of the futures contract and the underlying asset should eventually align. By exploiting these pricing disparities, futures arbitrageurs seek to make risk-free profits through the simultaneous buying and selling of contracts. This strategy requires quick execution and sophisticated analysis to identify and capitalize on profitable opportunities in the futures market.

3.3.5. Cross-Border Arbitrage

It is a trading strategy that involves taking advantage of price differentials or inefficiencies in financial instruments or assets across different countries or jurisdictions. Traders engaging in cross-border arbitrage exploit variations in prices, exchange rates, interest rates, or regulatory discrepancies between markets to generate profits [21]. This strategy typically involves buying in one market where the price is lower and simultaneously selling in another market where the price is higher to capitalize on the price differential. Cross-border arbitrage requires an understanding of international markets, currency exchange rates, and regulatory frameworks to identify and execute profitable trades.

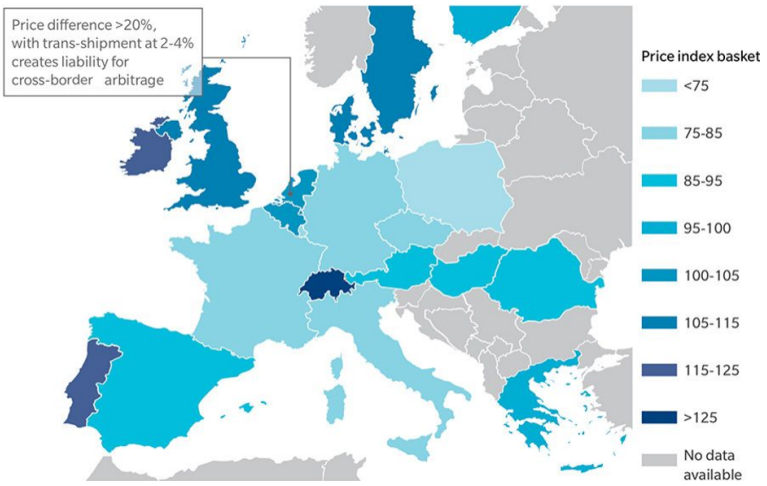

Figure 10: Cross-Border Arbitrage from Revenue.AI

3.3.6. OTC Arbitrage

It is a trading strategy that involves exploiting price discrepancies or inefficiencies in financial instruments traded outside of formalized exchanges. Unlike

exchange-traded assets, OTC instruments are negotiated directly between parties without the involvement of a centralized exchange. OTC arbitrageurs seek to profit from differences in prices, interest rates, or other relevant factors across different OTC markets. This strategy typically involves identifying mispricings, negotiating favorable terms, and executing trades to capture the price differential. OTC arbitrage can be complex and may require strong relationships, market knowledge, and access to liquidity providers to successfully execute trades and generate profits.

3.3.7. Token Swap Arbitrage

It is a trading strategy that takes advantage of price discrepancies between different decentralized exchanges or platforms when swapping or trading tokens. It involves identifying instances where the price of a token on one platform is significantly different from its price on another platform. Arbitrageurs execute trades by buying the token at a lower price and selling it at a higher price, aiming to capture the price difference as profit. This strategy relies on the speed and efficiency of decentralized exchanges and requires careful monitoring of token prices and transaction costs to identify and exploit arbitrage opportunities.

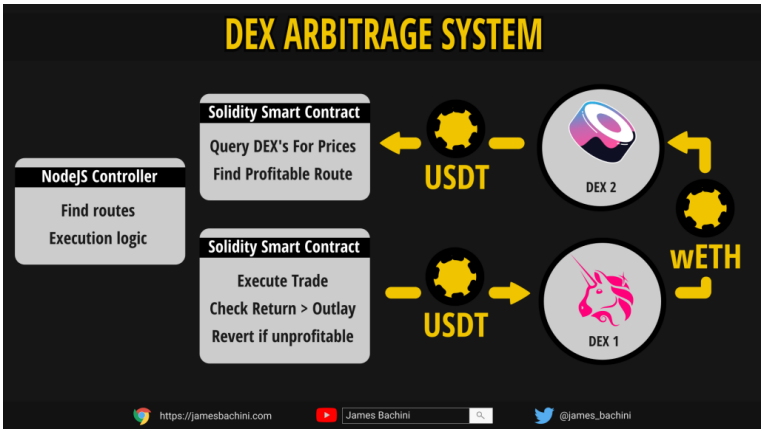

Figure 11: DEX Arbitrage System by James Bachini

3.3.8. ICO Arbitrage

It is a trading strategy that seeks to profit from price discrepancies and variations in tokens offered during different ICOs. It involves identifying instances where the same or similar tokens are available for purchase at different prices during different ICO campaigns. Arbitrageurs participating in ICO arbitrage aim to buy tokens at a

lower price from one ICO and sell them at a higher price in another ICO or on secondary markets. This strategy requires thorough research, analysis, and understanding of the tokens, ICO projects, and market trends to identify profitable arbitrage opportunities. It is important to note that ICO arbitrage carries inherent risks, including regulatory considerations and the potential for illiquid markets.

3.3.9. Cash and Carry Arbitrage

It is a trading strategy that exploits price differentials between a futures contract and its underlying asset, typically in commodities or financial markets. The strategy involves simultaneously buying the underlying asset in the spot market and selling a corresponding futures contract [22]. Arbitrageurs can lock in a risk-free profit by taking advantage of the price disparity between the two markets. The "carry" aspect refers to the cost of holding the asset until the futures contract expires. This strategy relies on efficient execution, accurate cost calculations, and the ability to store or finance the underlying asset until the futures contract matures.

Figure 12: Cash and Carry Arbitrage from Finance Strategists

3.3.10. Market Maker Arbitrage

It is a trading strategy used by market makers to profit from temporary price discrepancies or imbalances in the bid-ask spread of a financial instrument. Market makers, who provide liquidity by continuously buying and selling securities, take advantage of moments when the bid price (the price buyers are willing to pay) exceeds the asking price (the price sellers are willing to accept) or vice versa [23]. By quickly executing trades to buy at the lower price and sell at the higher price, market makers can capture the spread as profit. This strategy requires sophisticated technology, fast execution, and a deep understanding of the market dynamics to identify and exploit these fleeting opportunities.

4. Methodology

To facilitate the development of cryptocurrency arbitrage, the following sub-topics encompass the experimental criteria.

4.1. Data Collection

Real-time data will be collected through Binance. It will calculate the delay for each arbitrage path. Also, profit will be presented in percentages. Executed orders will be recorded on Google Sheets through Google APIs for analysis.

Provider	Binance
Period	• 2023-10-22 - 12:45 am (From) • 2023-11-05 - 12:45 am (To)
Refresh Rate	5000 ms
Interval	Real-time
Dataset	Order Book 1. Quantity 2. Ask Price 3. Bid Price

Calculation	1. Delay 2. Path 3. Profit

Table 1: Context of the Data

4.2. Framework

Within the realm of software development, a remarkable endeavor unfolds in the form of two distinct Node.js applications known as Trading Gate and Generic Backend. While Trading Gate harnesses the expressive power of JavaScript, Generic Backend embraces the refined capabilities of TypeScript.

Trading Gate
Programming Language
• JavaScript
Dependency
1. "blessed": "^0.1.81", 2. "node-binance-api": "^0.11.11", 3. "nodemon": "^3.0.1", 4. "pino": "^6.11.1", 5. "pino-pretty": "^4.5.0"

Table 2: Details of Trading Gate

Trading Gate emerges as a catalyst for empowerment, enabling users to engage in the enthralling realm of real and simulated trading on Binance. With its intricate architecture, users are bestowed with the tools to navigate the dynamic landscape of financial markets.

Generic Backend
Programming Language

• TypeScript	
Dependency	**Dev Dependency**
1. "@aws-sdk/client-s3": "^3.427.0", 2. "@fastify/express": "^2.3.0", 3. "cors": "^2.8.5", 4. "express": "^4.18.2", 5. "fastify": "^4.15.0", 6. "firebase": "^9.17.1", 7. "googleapis": "^110.0.0", 8. "mongoose": "^6.8.4", 9. "mysql": "^2.18.1", 10. "mysql2": "^3.6.1", 11. "node-fetch": "^2.6.1", 12. "pg": "^8.10.0", 13. "redis-om": "^0.3.6", 14. "ws": "^8.13.0"	1. "@types/cors": "^2.8.13", 2. "@types/express": "^4.17.16", 3. "@types/mysql": "^2.15.22", 4. "@types/node": "^18.15.11", 5. "@types/node-fetch": "^2.6.2", 6. "@types/pg": "^8.6.6", 7. "@types/ws": "^8.5.4", 8. "nodemon": "^2.0.20", 9. "ts-node": "^10.9.1", 10. "typescript": "^4.9.4"

Table 3: Details of Generic Backend

On the other hand, Generic Backend presents itself as an exquisite utility, facilitating the seamless recording of data across a diverse array of backends. These backends encompass the realms of MySQL, Firebase, Firestore, MongoDB, PostgreSQL, Google Sheets, and Redis. However, for the sake of simplicity and streamlined analytics, the illustrious domain of Google Sheets stands as the chosen bastion for capturing and analyzing data.

In this harmonious convergence of innovation, Trading Gate and Generic Backend coalesce to form a symphony of technological prowess, enabling users to embark on trading adventures while effortlessly capturing and harnessing the power of data.

4.3. Initial Account Setting

Only demo trading is employed. However, traders could consider an initial capital of HKD 2000, which meets the minimum trading amount requirement of Binance.

4.4. Commission

Commission fees for spot and margin trading are determined by the trading volumes and individual capital. Typically, a flat fee of 0.1% is levied per trade for regular traders. Below are the specific breakdowns.

Level	30d Trade Volume (BUSD)	and/or	BNB Balance	Maker / Taker
Regular User	< 1,000,000 BUSD	or	≥ 0 BNB	0.1000% / 0.1000%
VIP 1	≥ 1,000,000 BUSD	and	≥ 25 BNB	0.0900% / 0.1000%
VIP 2	≥ 5,000,000 BUSD	and	≥ 100 BNB	0.0800% / 0.1000%
VIP 3	≥ 20,000,000 BUSD	and	≥ 250 BNB	0.0420% / 0.0600%
VIP 4	≥ 100,000,000 BUSD	and	≥ 500 BNB	0.0420% / 0.0540%
VIP 5	≥ 150,000,000 BUSD	and	≥ 1,000 BNB	0.0360% / 0.0480%
VIP 6	≥ 400,000,000 BUSD	and	≥ 1,750 BNB	0.0300% / 0.0420%

VIP 7	≥ 800,000,000 BUSD	and	≥ 3,000 BNB	0.0240% / 0.0360%
VIP 8	≥ 2,000,000,000 BUSD	and	≥ 4,500 BNB	0.0180% / 0.0300%
VIP 9	≥ 4,000,000,000 BUSD	and	≥ 5,500 BNB	0.0120% / 0.0240%

Table 4: Commission Calculation for Binance

$$TotalCommissionPercentage = (1 + \text{Commission Percentage})^n - 1$$

Where

1. Commission Percentage = 0.1% = 0.001
2. n = Number of trades

Hence, when engaging in triangular arbitrage with a fee of 0.1% per trade and executing three trades, the resulting total commission percentage amounts to approximately 0.3003%, deriving from the expression (1 + 0.001)^3 - 1.

4.5. Ideation

To ensure the local order book remains synchronized, web socket connections are utilized. However, upon app initialization, the order book for each monitored symbol necessitates initialization. This task is accomplished by soliciting an order book snapshot from Binance through a REST call. It is important to note that these REST requests carry weight, and if the scanning depth value is excessively large, the delay may be increased. This is due to Binance requiring more time for higher depth values.

4.5.1. Mutable Configuration

Trading Gate incorporates a JSON structure that encapsulates the modifiable components of trading strategies. To access real-time data feeds from Binance, a valid account is required. Once authenticated, the base currency for arbitrage can be specified, indicating the starting and ending currencies for the arbitrage process. The algorithm seamlessly scans the market with the predefined market depth, automating the search for profitable opportunities. Furthermore, a watchlist can be defined to exclusively monitor the specified symbols, narrowing down the focus of the trading activities.

Trading Gate


```
{
  "url": {
    "backend": ""
  },
  "binance_option": {
    "APIKEY": "",
    "APISECRET": "",
    "test": true,
    "verbose": true
  },
  "fund": {
    "USDT": {
      "MIN": 50,
      "MAX": 750,
      "STEP": 50
    }
  },
  "scanner": {
    "depth": 100,
    "whitelist": [
      "USDT",
      "BTC",
```

```
        "MATIC",
        "BUSD",
        "ONE",
        "HOT",
        "BRL",
        "BTT",
        "TRX",
        "WIN",
        "BNB",
        "XLM",
        "DAI",
        "YFI",
        "DOGE",
        "STRAX"
    ]
},
"script": {
    "max_trade": 1000,
    "strategy": "parallel",
    "template": [
        "*",
        "*",
        "*"
    ],
    "fee": 0,
    "threshold": {
        "profit_percent": 0.3,
        "delay_ms": 25
    }
},
"panel": {
    "allow": true,
    "row_num": 10,
```

```
    "refresh_ms": 5000
  },
  "message": {
    "verbose": "debug",
    "beautify": true,
    "status_refresh_min": 2
  },
  "web_socket": {
    "ticket_num": 1,
    "init_delay_ms": 200
  }
}
```

Table 5: Trading Gate Configuration

The Generic Backend encompasses a JSON structure that encapsulates operations related to authentication, cryptography, database, and storage. This backend architecture is designed to seamlessly accommodate requests from diverse frontends, each with its unique set of functionalities. It boasts an extensive repertoire of over 80 cryptographic functions, enabling robust encryption and decryption capabilities. Additionally, it facilitates Create, Read, Update, and Delete (CRUD) operations across multiple database service providers, offering the flexibility to interact with various data storage systems.

Generic Backend

```
{
  "service": {
    "provider": "",
    "action": "",
    "password": "",
    "crypto": {
      "name": "aria-128-cfb8",
      "type": "encrypt"
```

```
    },
    "hash": [],
    "validation": [],
    "node": "database.collection.node"
},
"data": {},
"key": {
    "mysql": {},
    "firebase": {},
    "postgre_sql": {},
    "google": {},
    "mongodb": {},
    "redis": {}
},
"crypto": {
    "key": {
        "public": {
            "value": "public",
            "length": 32
        },
        "private": {
            "value": "private",
            "length": 16
        }
    },
    "salt": {
        "value": "salt",
        "length": 16
    },
    "iv": {
        "value": "iv",
        "length": 16
    },
```

```
    "limit": 5,
    "option": {
      "N": 16384,
      "r": 8,
      "p": 1,
      "maxmem": 33554432
    }
  }
}
```


Table 6: Generic Backend Configuration

4.5.2. Realtime Panel

An advanced real-time panel is meticulously crafted to provide an immersive visualization of the expansive triangular arbitrage landscape. Through meticulous calculations, the panel determines the latency associated with each arbitrage action, crucial in assessing its feasibility. A lower latency is avidly sought, denoting an enhanced potential for successful arbitrage execution. Furthermore, the panel undertakes precise profit calculations for every available arbitrage path, enabling comprehensive ranking that empowers astute investors to swiftly identify and capitalize on the most lucrative opportunities within the market.

Delay [A-B]	Delay [B-C]	Delay [C-A]	Delay [Max]	Path	Profit
2081	1581	80	2081	USDT-BUSD-BNB	-0.3398%
80	2782	881	2782	USDT-BNB-TRX	-0.3483%
280	280	80	280	USDT-MATIC-BNB	-0.3777%
...	...	...	...	...	...

Table 7: Real-time Panel for Triangular Arbitrage

4.6. Strategies

Suppose we have the following order book data for three currency pairs: A/B, B/C, and C/A.

Order Book					
A/B		**B/C**		**C/A**	
Best Bid Price	Best Ask Price	Best Bid Price	Best Ask Price	Best Bid Price	Best Ask Price
1.4999	1.5001	0.7999	0.8001	1.9999	2.0001

Table 8: Simulation of Order Book

In triangular arbitrage, the basic principle is that the product of the exchange rates for the three currency pairs involved in the arbitrage loop should be greater than 1. If the product is greater than 1, there is a potential for profit through arbitrage.

$$\frac{1}{\text{Exchange Rate}AB} \times \frac{1}{\text{Exchange Rate}BC} \times \text{Exchange Rate}_{AC} > 1$$

Where

1. $(\text{Exchange Rate}_{AB})$ represents the exchange rate between Currency A and Currency B.
2. $(\text{Exchange Rate}_{BC})$ represents the exchange rate between Currency B and Currency C.
3. $(\text{Exchange Rate}_{AC})$ represents the exchange rate between Currency A and Currency C.

Calculation

1.4999 * 0.8001 * 2.0001 = 2.3998 > 1

Path

1. Sell Currency A for Currency B at the best ask price (1.5001 A/B).
2. Sell Currency B for Currency C at the best bid price (0.7999 B/C).
3. Sell Currency C for Currency A at the best bid price (1.9999 C/A).

To determine if an arbitrage opportunity exists, we need to check if the bid price of A/B multiplied by the ask price of B/C multiplied by the ask price of C/A is greater than 1. In this example, the result is 2.3998, which is greater than 1. Therefore, there is a triangular arbitrage opportunity. By completing this triangular loop, you would end up with more of Currency A than you started with, resulting in a profit.

<table>
<tr><th colspan="3">Action Combination</th></tr>
<tr><th>Sell, Sell, Sell</th><th>Buy, Buy, Buy</th><th>Sell, Buy, Sell</th></tr>
<tr>
<td>1. Sell Currency A for Currency B at the ask price.
2. Sell Currency B for Currency C at the ask price.
3. Sell Currency C for Currency A at the bid price.</td>
<td>1. Buy Currency A with Currency B at the bid price.
2. Buy Currency B with Currency C at the bid price .
3. Buy Currency C with Currency A at the ask price.</td>
<td>1. Sell Currency A for Currency B at the ask price.
2. Buy Currency B with Currency C at the bid price.
3. Sell Currency C for Currency A at the bid price.</td>
</tr>
<tr><th>Buy, Sell, Buy</th><th>Sell, Buy, Buy</th><th>Buy, Sell, Sell</th></tr>
<tr>
<td>1. Buy Currency A with Currency B at the bid price.
2. Sell Currency B for Currency C at the ask price.</td>
<td>1. Sell Currency A for Currency B at the ask price.
2. Buy Currency B with Currency C at the bid price.</td>
<td>1. Buy Currency A with Currency B at the bid price.
2. Sell Currency B for Currency C at the ask price.</td>
</tr>
</table>

3. Buy Currency C with Currency A at the ask price.	3. Buy Currency C with Currency A at the bid price.	3. Sell Currency C for Currency A at the ask price.

Table 9: Action Combination for Triangular Arbitrage

These steps outline the sequence of trades for each combination in triangular arbitrage. It's important to note that executing these trades requires precision in timing, low transaction costs, and fast execution due to the short-term nature of the strategy. Additionally, market conditions and liquidity can significantly impact the effectiveness of triangular arbitrage.

Order Execution	
Sequential	**Concurrent**
Three trades are sequentially executed, one after the other.	Three trades were triggered at once.

Table 10: Trading Behaviours for Triangular Arbitrage

As shown in the table above, orders will executed in sequential and concurrent manners.

4.6.1. Strategy 1 - Sequential Execution

The initiation of the three trades occurs sequentially, with each subsequent trade being executed upon the completion of the preceding one.

Pros	**Cons**
Simplicity Sequential execution follows a straightforward and linear process, making it easier to understand and	Longer Execution Time Sequential execution prolongs the overall execution time, as each subsequent trade can only begin after

implement.	the completion of the previous one.
Reduced Risk By executing trades sequentially, each trade's outcome can be evaluated before proceeding to the next one, reducing the risk of simultaneous unfavorable outcomes.	Missed Opportunities While waiting for the completion of each trade, potentially profitable opportunities in other symbols may arise but cannot be captured immediately.
Lower Capital Requirement Since only one symbol's balance needs to be held, the initial capital required for trading is typically lower compared to concurrent execution.	

Table 11: Pros and Cons of Sequential Execution

Because each trade uses the balance acquired from the previous trade, a balance of only one symbol must be held. For instance, if USDT-BNB-ETH is identified as profitable, only the base symbol of USDT would need to be held.

4.6.2. Strategy 2 - Concurrent Execution

Simultaneous initiation of all three trades results in a reduction of the total execution time, encompassing the entire process from identification to completion.

Pros	Cons
Faster Execution Time Concurrent execution allows all trades to be initiated simultaneously, resulting in a shorter overall execution time.	Increased Complexity Concurrent execution introduces greater complexity, requiring advanced monitoring and management of multiple trades simultaneously.

Capital Efficiency	Higher Risk
By executing multiple trades concurrently, capital can be deployed more efficiently, potentially maximizing profit opportunities.	The risk of adverse outcomes is amplified with concurrent execution, as unfavorable market movements can impact multiple trades simultaneously.
Enhanced Portfolio Diversification	Higher Capital Requirement
Concurrent execution enables the simultaneous utilization of multiple symbols, providing better diversification within the trading strategy.	Maintaining balanced portfolios for all symbols involved necessitates a higher initial capital investment compared to sequential execution.

Table 12: Pros and Cons of Concurrent Execution

To execute simultaneous trades, it is necessary to maintain a balanced portfolio of all symbols involved. For example, if ETH-DOGE-ETH is identified as a profitable opportunity, it is essential to hold a sufficient balance of ETH, DOGE, and ETH. Each balance should be large enough to cover the maximum potential quantity that could be exchanged for the respective symbol.

4.7. Steps

To streamline the process of Triangular Arbitrage, the implementation leverages a set of pivotal steps listed below.

Step 1
$$\text{Cross Rate} = \frac{\text{Direct Quote of Currency A in Base Currency}}{\text{Direct Quote of Currency B in Base Currency}}$$ • Calculate the cross rate between two currencies given their respective direct quotes

Or

$$\text{Cross Rate} = \frac{1}{\text{Indirect Quote of Currency A in Base Currency}} \times \frac{\text{Indirect Quote of Currency B in Base Currency}}{1}$$

- Calculate the cross rate between two currencies given their respective indirect quotes

Step 2

$$\text{Opportunity Factor} = \text{Cross Rate} - 1$$

- Calculate the triangular arbitrage opportunity factor

Step 3

$$\text{Base Currency Amount} = \frac{\text{Initial Balance}}{\text{Cross Rate}}$$

- Determine the base currency amount needed for triangular arbitrage

Step 4

$$\text{Intermediary Currency Amount} = \text{Base Currency Amount} \times \text{Cross Rate}$$

- Calculate the intermediary currency amount obtained in triangular arbitrage

Step 5

$$\text{Adjusted Intermediary Currency Amount} = \text{Intermediary Currency Amount} \times (1 - \text{Transaction Cost Percentage})$$

• Adjust the intermediary currency amount for transaction costs
Step 6
$$\text{Quote Currency Amount} = \text{Adjusted Intermediary Currency Amount} \times \text{Cross Rate}$$ • Calculate the final quote currency amount obtained in triangular arbitrage
Step 7
$$\text{Profit} = \text{Quote Currency Amount} - \text{Initial Balance}$$ • Calculate the triangular arbitrage profit
Step 8
$$\text{ROI} = \frac{\text{Profit}}{\text{Initial Balance}} \times 100$$ • Calculate the triangular arbitrage return on investment (ROI)
Step 9
$$\text{Break-Even Percentage Change} = \left(\frac{1}{\text{Opportunity Factor}}\right) \times 100$$ • Determine the break-even percentage change in exchange rates for a profitable triangular arbitrage

Table 13: Steps for Triangular Arbitrage

4.8. Analytical Metrics

To assess the profitability of the strategies, meticulous attention will be devoted to the measurement of key metrics. Herein, we elucidate the contextual significance of each metric.

Price Discrepancy Identification	Tracking the frequency and accuracy with which the algorithm identifies price discrepancies or arbitrage opportunities among different currency pairs can provide insights into its effectiveness.
Trade Execution Speed	Measuring the algorithm's speed in executing trades can help assess its efficiency in capitalizing on arbitrage opportunities before they disappear.
Simulation Results	By simulating the algorithm's trades based on historical data and evaluating the outcomes, it is possible to assess the potential profitability and performance if real money were involved.
Risk Analysis [Deprecated]	Evaluating the algorithm's risk management capabilities, including metrics such as drawdown and volatility, can help identify potential risks and areas for improvement.
Statistical Analysis [Deprecated]	Utilizing statistical measures such as the Sharpe ratio, Sortino ratio, or information ratio can help assess the risk-adjusted performance and potential for improvement of the algorithm.

Table 14: Description of Analytical Metrics

4.8.1. Order Book Inspection

Through astute analysis of the order book information, traders possess the means to unveil the latent profitability concealed within the realm of triangular arbitrage. Attentively scrutinizing the interplay of prices and volumes across diverse levels, they discern the telltale signs of potential. When a substantial discrepancy materializes, illuminating a tantalizing opportunity for arbitrage, traders deftly orchestrate the seamless execution of synchronized buy and sell orders across the triad of currency pairs. They deftly navigate the labyrinth of market inefficiencies, harnessing their essence to artfully cultivate profit from the fertile grounds of disparity.

$$\text{Order Book Inspection} = \sum_{i=1}^{n} (P_i \cdot V_i)$$

where

1. (n) : Number of price levels in the order book
2. (P_i) : Price at level (i)
3. (V_i) : Volume at level (i)

```
get_order_book_depth_requirement(method, quantity, depthSnapshot) {
let exchanged = 0;
let rates;

if (method === "SELL") {
rates = Object.keys(depthSnapshot.bids || {});
} else if (method === "BUY") {
rates = Object.keys(depthSnapshot.asks || {});
} else {
throw new Error(`Unknown method: ${method}`);
}

for (let i = 0; i < rates.length; i++) {
exchanged +=
method === "SELL"
? depthSnapshot.bids[rates[i]]
: depthSnapshot.asks[rates[i]];
```

```
if (exchanged >= quantity) {
return i + 1;
}
}
return rates.length;
}
```

Code snippet 1: Calculation of Order Book Depth

4.8.2. Crypto Dust

In the realm of triangular arbitrage, dust assets are the minute remnants of fractional units or fractional currencies that are left behind in the process of executing trades. These trace amounts, often disregarded as inconsequential, may arise from rounding errors or imprecise calculations during the arbitrage transaction. While individually negligible, these minuscule fragments possess a hidden allure. Perceptive traders recognize that even these seemingly insignificant remnants hold the potential to collectively contribute to profitable opportunities.

$$\text{Dust Assets} = \text{Total Assets} - (\text{Whole Assets} \times \text{Floor})$$

```
calculate_dustless(amount, dustDecimals) {
if (Number.isInteger(amount)) return amount;
const amountString = amount.toFixed(12);
const decimalIndex = amountString.indexOf(".");
return parseFloat(amountString.slice(0, decimalIndex + dustDecimals + 1));
}
```

Code snippet 2: Calculation of Dust Asset

4.8.3. Quote Conversion

In the intricate domain of triangular arbitrage, direct and indirect quotes serve as the elegant conduits through which currency exchange rates are expressed. A direct quote expresses the value of one unit of a domestic currency in terms of a foreign currency, illuminating the relative strength of the domestic currency. An indirect quote, on the other hand, articulates the value of one unit of a foreign currency in relation to the domestic currency, providing insights into the relative strength of the foreign currency.

$$\text{Direct Quote of Token A in Token B} = \frac{1}{\text{Indirect Quote of Token B in Token A}}$$

```
direct_or_indirect_quote(amountFrom, rate, quantity, isDirect) {
if (isDirect) {
if (quantity < amountFrom) {
amountFrom -= quantity;
return [amountFrom, quantity * rate];
} else {
return [0, amountFrom * rate];
}
} else {
const exchangeableAmount = quantity * rate;
if (exchangeableAmount < amountFrom) {
amountFrom -= exchangeableAmount;
return [amountFrom, quantity];
} else {
return [0, amountFrom / rate];
}
}
}
```

Code snippet 3: Determination of Direct or Indirect Quote

4.8.4. Execution

Upon the identification of a lucrative triangular arbitrage opportunity in the forex market, the process of executing a market order for buying or selling unfolds. The trade size is carefully calculated, taking into account available capital and risk management strategies, ensuring optimal allocation of resources. Finally, the market order is swiftly placed, enabling the simultaneous execution of buy or sell orders for the involved currency pairs.

$$\text{Market Order} = \text{Volume} \times \text{Market Price}$$

where

1. (Volume) represents the quantity or volume of the asset being traded, and

2. (Market Price) represents the prevailing price at which the market order is executed.

```
async market_buy(ticker, quantity) {
logger.execution.info(
`${
binance.getOption("test") ? "Test: Buying" : "Buying"
} ${quantity} ${ticker} @ market price`
);
const before = Date.now();
try {
const response = await binance.marketBuy(ticker, quantity, {
type: "MARKET",
});
if (binance.getOption("test")) {
logger.execution.info(
`Test: Successfully bought ${ticker} @ market price`
);
} else {
logger.execution.info(
`Successfully bought ${response.executedQty} ${ticker} @ a quote of ${
response.cummulativeQuoteQty
} in ${utility.ms_since(before)} ms`
);
}
return response;
} catch (error) {
return binance_api.buy_or_sell_error(error);
}
}
```

Code snippet 4: Buying with Market Order

```
async market_sell(ticker, quantity) {
logger.execution.info(
`${
binance.getOption("test") ? "Test: Selling" : "Selling"
} ${quantity} ${ticker} @ market price`
);
```

```
try {
const before = Date.now();
const response = await binance.marketSell(ticker, quantity, {
type: "MARKET",
});
if (binance.getOption("test")) {
logger.execution.info(
`Test: Successfully sold ${ticker} @ market price`
);
} else {
logger.execution.info(
`Successfully sold ${response.executedQty} ${ticker} @ a quote of ${
response.cummulativeQuoteQty
} in ${utility.ms_since(before)} ms`
);
}
return response;
} catch (error) {
return binance_api.buy_or_sell_error(error);
}
}
```

Code snippet 5: Selling with Market Order

5. Performance Evaluation

5.1. Visualization

The embodiment of trading strategy prowess shall manifest in captivating visualizations, as performance is unveiled through the below parameters.

Delay	Occurrence	Trading History
The time between identifying opportunity and executing trades in triangular arbitrage.	The emerging frequency of specific paths for triangular arbitrage.	Record of executed trades, including time, currency pairs, volumes, prices, and profits/losses in triangular arbitrage.

Table 15: Metrics for Visualization

5.1.1. Strategy 1 - Sequential Execution

Data segment of the sequential execution strategy can be found in Appendix A.

5.1.1.1. Delay

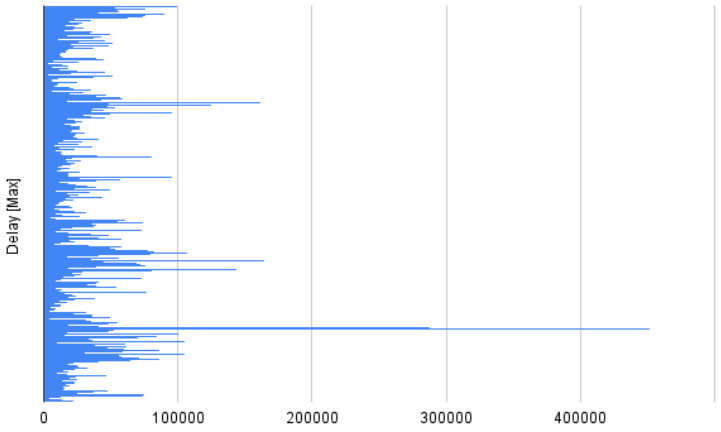

Figure 13: Delay of Sequential Execution

Delay			
Path	**Avg**	**Max**	**Min**
A-B	3131.019873 ms	171245 ms	1 ms
B-C	3056.735112 ms	675166 ms	7 ms
C-A	3948.86772 ms	283594 ms	1 ms

Table 16: Delay of Sequential Execution

The duration of an arbitrage delay for each path ranges between 3 to 4 seconds. While these delays may appear brief, they significantly hinder our ability to seize lucrative arbitrage opportunities. Ideally, a profitable arbitrage should be executed within a mere 25 milliseconds, ensuring swift and advantageous transactions. Consequently, our slower machine is consistently outmatched by its faster counterparts, resulting in a substantial number of unattainable trades.

5.1.1.2. Occurrence

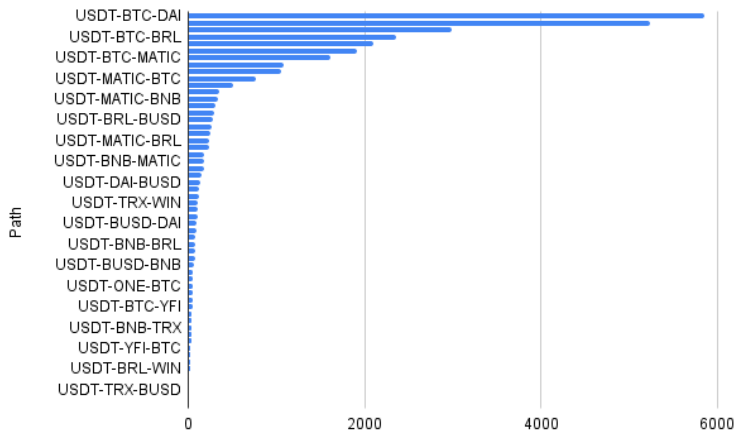

Figure 14: Occurrence of Sequential Execution

Occurrence	
Path	**Frequency**
USDT-BTC-DAI	5848
USDT-BRL-BTC	5241
USDT-DAI-BTC	2986
USDT-BTC-BRL	2356
USDT-BNB-BTC	2101

Table 17: Occurrence of Sequential Execution

The three most notable arbitrage paths encompass USDT-BTC-DAI, USDT-BRL-BTC, and USDT-DAI-BTC. Traditionally, cryptocurrencies with substantial trading volumes present greater potential, as they tend to exhibit narrower spreads. As an intermediate currency, BTC is favored by the system due to its widespread adoption and liquidity. Throughout the testing phase, DAI has demonstrated a bullish trend, indicating a positive market sentiment. Conversely, BRL has been subject to pronounced bearish trends, suggesting a challenging and volatile landscape. Consequently, the arbitrage path within the system is characterized by heightened volatility, necessitating careful consideration and risk management.

5.1.1.3. Trading History

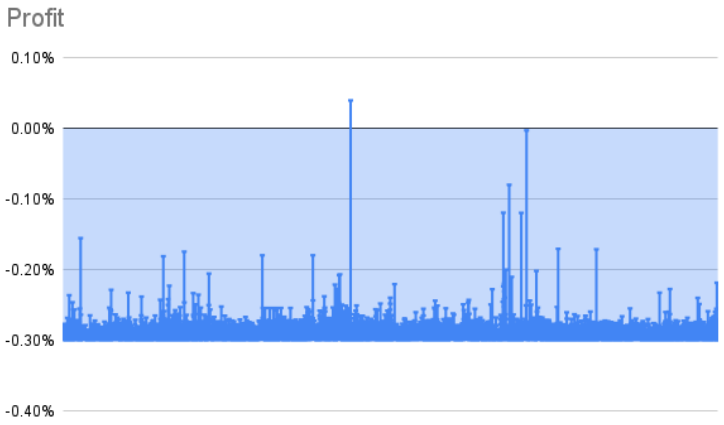

Figure 15: Trading History of Sequential Execution

Trading History			
Total Trade	Profit		
	Avg	Max	Min
30443	-0.29%	0.04%	-0.30%

Table 18: Trading History of Sequential Execution

The system adeptly identifies a lucrative trading path that yields a maximum profit of 0.04%, accounting for all associated commissions. Nevertheless, the average profit stands at -0.29%, implying that profitable arbitrage opportunities are infrequent and elusive. It is noteworthy that despite the negative profit recorded, our system refrains from initiating new trades when the profit falls below the commission threshold. Instead, these instances of negative profit signify trades that, while potentially profitable, fail to surpass the commission barrier.

5.1.2. Strategy 2 - Concurrent Execution

Data segment of the concurrent execution strategy can be found in Appendix B.

5.1.2.1. Delay

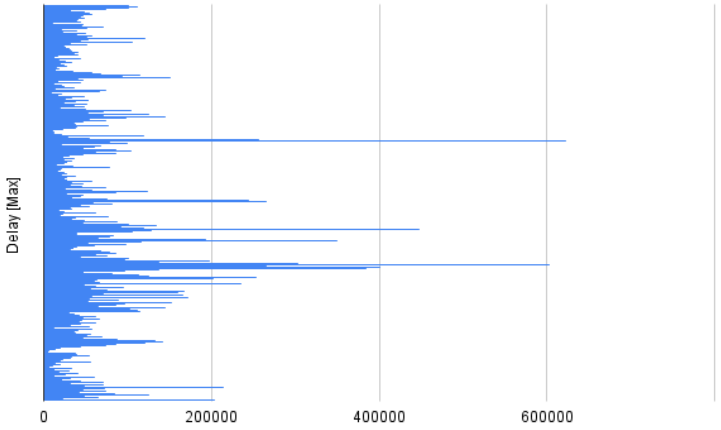

Figure 16: Delay of Concurrent Execution

Delay			
Path	**Avg**	**Max**	**Min**
A-B	3151.355331 ms	166781 ms	3 ms
B-C	3347.852925 ms	622997 ms	14 ms
C-A	3930.292176 ms	303250 ms	2 ms

Table 19: Delay of Concurrent Execution

Arbitrage delays, encompassing a temporal span of approximately 3 to 4 seconds for each path, present a formidable challenge to seizing lucrative arbitrage opportunities. Despite their ephemeral nature, these intervals significantly hinder our ability to leverage profitable prospects. Enhancing performance entails deploying the arbitrage strategy on the cloud, utilizing a server positioned near the Binance exchange. The proximity to the exchange directly correlates with heightened trading speed, optimizing our ability to swiftly execute trades and maximize profitability.

5.1.2.2. Occurrence

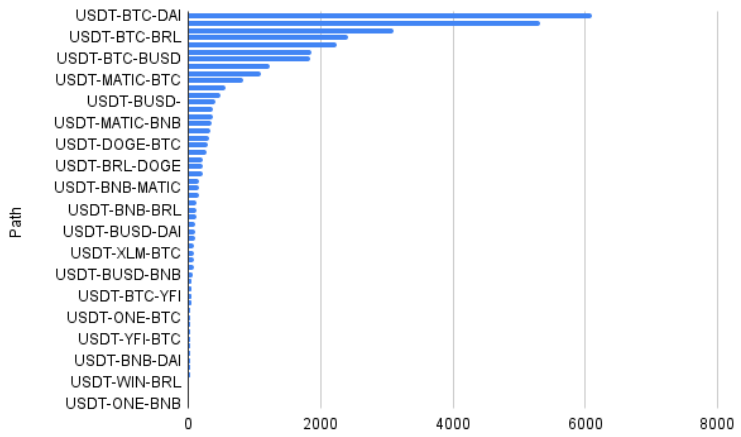

Figure 17: Occurrence of Concurrent Execution

Occurrence	
Path	**Freq**
USDT-BTC-DAI	6096
USDT-BRL-BTC	5322
USDT-DAI-BTC	3095
USDT-BTC-BRL	2411
USDT-BNB-BTC	2244

Table 20: Occurrence of Concurrent Execution

The preeminent trio of arbitrage paths encompasses USDT-BTC-DAI, USDT-BRL-BTC, and USDT-DAI-BTC. Per convention, cryptocurrencies endowed with substantial trading volumes unveil heightened prospects, primarily due to their propensity for narrower spreads. The system bestows favor upon BTC as an intermediary currency, given its widespread adoption and commendable liquidity. During the rigorous testing phase, DAI has unveiled a bullish trajectory, signifying a prevailing positive market sentiment. Conversely, BRL has weathered pronounced bearish trends, indicating a landscape fraught with challenges and volatility. Consequently, the arbitrage path embedded within the system assumes an aura of amplified volatility, necessitating prudent deliberation and astute risk management.

5.1.2.3. Trading History

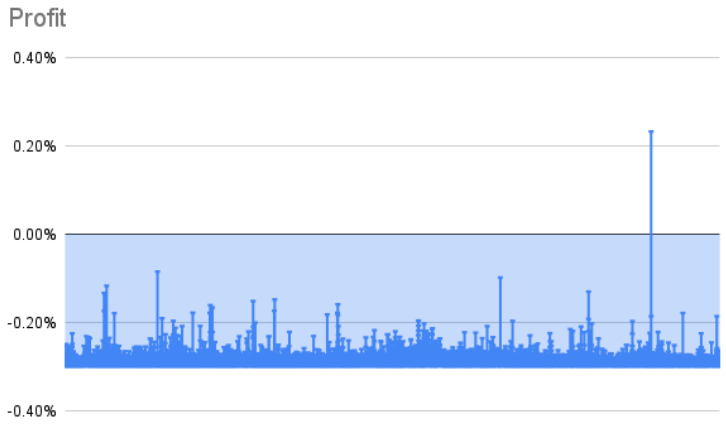

Figure 18: Trading History of Concurrent Execution

Trading History			
Total Trade	Profit		
	Avg	Max	Min
32412	-0.29%	0.23%	-0.30%

Table 21: Trading History of Concurrent Execution

The highest attainable profit, inclusive of all associated commissions, amounts to 0.23%. Furthermore, the average profit remains at -0.29%, indicating the scarcity and elusive nature of profitable arbitrage opportunities. It is important to highlight that despite the presence of negative profit, our system exercises prudence by abstaining from initiating new trades when the profit falls below the commission threshold. These instances of negative profit signify trades that, although potentially profitable, do not surpass the commission barrier.

5.2. Evaluation

By toggling the parameter within the configuration JSON, the system can seamlessly transition into executing live trades. Nonetheless, to mitigate potential losses and prioritize the development of a refined system, the current focus lies solely on conducting paper trading.

5.2.1. Sequential Execution VS Concurrent Execution

While sequential and concurrent execution proves profitable, both systems exhibit indistinguishable performance. Their minimum and average profits align, as do their chosen arbitrage paths and delays. However, concurrent execution introduces added risks by necessitating the possession of the associated cryptocurrency in the arbitrage path. This exposes the profit directly to the potential downsides of holding those particular assets. Consequently, prioritizing sequential execution is recommended as it circumvents market exposure for the opened position, safeguarding against potential risks.

5.2.2. Sequential Execution VS Passive ETF Investing

Year	RSP	SPY	RSP vs. SPY
2004	10.28%	6.12%	4.16%
2005	15.28%	9.81%	5.48%
2006	13.66%	14.83%	-1.17%
2007	-5.70%	-2.67%	-3.03%
2008	-42.59%	-38.25%	-4.34%
2009	52.55%	32.65%	19.90%
2010	28.18%	22.18%	6.00%
2011	2.81%	4.19%	-1.38%
2012	18.08%	16.52%	1.55%
2013	23.49%	21.43%	2.06%
2014	14.11%	14.12%	-0.01%
2015	-5.31%	-0.87%	-4.44%
2016	23.68%	19.98%	3.70%
2017	21.28%	26.30%	-5.03%
2018	-3.05%	-2.43%	-0.62%
2019	15.17%	21.45%	-6.27%
2020	23.21%	25.42%	-2.21%
Total	**365.95%**	**350.77%**	**15.18%**

Figure 19: Total Return of RSP and SPY from Investing for Beginners 101

Passive ETF investment consistently outperforms triangular arbitrage in terms of profitability, as substantiated by robust statistical evidence and empirical data. Extensive studies and historical analyses consistently confirm the competitive edge of passive ETFs in delivering long-term returns, while triangular arbitrage yields relatively modest profits. Actively managed funds often fall short of surpassing

benchmark indices, as research reports indicate. In contrast, triangular arbitrage, targeting fleeting price disparities across markets, tends to generate more limited profits, with average percentages frequently below 1% due to market efficiency. Passive ETF investments, however, boast a track record of substantial returns over extended periods. Furthermore, the remarkable expansion of the global ETF market serves as an additional testament to their profitability, with trillions of dollars in assets under management. Therefore, the convergence of statistical evidence and empirical data consistently underscores the superior profit potential of passive ETF investment compared to triangular arbitrage.

6. Improvement

6.1. Hardware

Employing superior hardware is imperative when developing triangular arbitrage strategies. EC2 instances and laptop CPUs often lack the required speed and processing power for high-frequency trading. EC2's virtualized environment and shared resources introduce latency, while laptop CPUs struggle to keep up with the demanding computational needs. Additionally, exchanges may have direct connections to their servers, achieving close to zero latency. Consequently, retail developers engaging in triangular arbitrage face significant challenges in attaining profitable outcomes during intense competition, as the minimal latency advantage enjoyed by institutional traders can significantly impact potential profits. Thus, upgrading hardware becomes paramount to optimizing performance and gaining a competitive edge in the challenging landscape of triangular arbitrage.

6.2. Exchanges

Diversifying our trading activities beyond Binance yields compelling advantages, including enhanced liquidity, reduced counterparty risk, and access to unique trading pairs. Consider these notable exchanges: Coinbase Pro for regulatory compliance; Kraken for strong security, and transparency; Bitstamp for its longstanding reputation and reliable platform for major cryptocurrencies; Huobi Global as a prominent exchange offering a diverse range of options; and KuCoin with its extensive selection of altcoins, competitive fees, and vibrant trading community. Expanding to multiple exchanges enables us to leverage diverse liquidity pools, seize

profitable opportunities, and foster adaptability in our trading strategies.

6.3. Framework

The utilization of C++ for triangular arbitrage development eclipses Javascript due to its low-level nature, rendering meticulous memory management and unparalleled execution speed. C++'s streamlined syntax and efficient compiler optimizations empower the creation of intricate algorithms with superior computational efficiency. In contrast, Javascript's interpreted nature, runtime environment, and dynamic typing pose innate performance limitations, hindering its ability to deliver the blazing execution speeds demanded by latency-sensitive triangular arbitrage strategies. Furthermore, C++ offers a plethora of mature financial libraries and frameworks tailored specifically for algorithmic trading, facilitating seamless integration into trading systems. Embracing C++ bequeaths unrivaled performance, precise memory control, and access to robust financial libraries, nurturing the development of optimized and swift trading systems.

7. Conclusion

In conclusion, triangular arbitrage underscores the intricate interplay between human intelligence and dynamic market conditions, intertwining elegance and complexity in the pursuit of profit. By harnessing real-time data streams, traders adeptly navigate the ever-shifting landscape of cryptocurrency markets, leveraging their analytical skills and swift decision-making to identify and exploit fleeting price differentials across multiple currency pairs. This form of arbitrage showcases the synergy between human intuition, algorithmic trading systems, and the cutting-edge technology offered by platforms like Binance. Triangular arbitrage encapsulates the harmonious blend of human ingenuity and computational prowess, fueling the quest for financial gains amidst the fast-paced and ever-evolving realm of cryptocurrency trading.

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9. Appendix

A - Sequential Execution Segment

	A	B	C	D	E	F	G
27107	2023-11-02T13:44:18.061Z	623	622	625	625	USDT-BTC-BRL	0.04%
27108	2023-11-02T13:44:28.066Z	627	925	624	925	USDT-XLM-BNB	-0.29%
27109	2023-11-02T13:44:33.089Z	649	746	646	746	USDT-BUSD-BNB	-0.29%
27110	2023-11-02T13:44:53.146Z	596	696	3500	3500	USDT-BTC-BRL	-0.28%
27111	2023-11-02T13:45:23.201Z	642	2242	5043	5043	USDT-BUSD-BRL	-0.29%
27112	2023-11-02T13:46:48.267Z	1374	770	671	1374	USDT-BRL-BTC	-0.29%
27113	2023-11-02T13:46:58.270Z	1272	672	670	1272	USDT-BUSD-DOGE	-0.30%
27114	2023-11-02T13:48:13.310Z	2281	680	676	2281	USDT-DAI-BTC	-0.29%
27115	2023-11-02T13:48:38.319Z	674	674	675	675	USDT-BNB-BTC	-0.29%
27116	2023-11-02T13:49:43.333Z	1863	763	660	1863	USDT-DAI-BTC	-0.28%
27117	2023-11-02T13:50:33.370Z	673	777	876	876	USDT-DOGE-BUSD	-0.29%
27118	2023-11-02T13:51:08.393Z	781	784	681	784	USDT-WIN-BNB	-0.23%
27119	2023-11-02T13:51:23.425Z	1509	707	607	1509	USDT-BUSD-BTC	-0.30%
27120	2023-11-02T13:51:33.449Z	1327	19337	626	19337	USDT-WIN-BNB	-0.23%
27121	2023-11-02T13:53:08.536Z	3672	1071	668	3672	USDT-DAI-BTC	-0.30%
27122	2023-11-02T13:53:28.557Z	679	778	882	882	USDT-BTC-BRL	-0.29%
27123	2023-11-02T13:53:38.575Z	695	695	693	695	USDT-DAI-BTC	-0.30%
27124	2023-11-02T13:54:33.684Z	3476	8479	675	8479	USDT-WIN-TRX	-0.29%
27125	2023-11-02T13:54:48.696Z	3384	1183	680	3384	USDT-DAI-BTC	-0.29%
27126	2023-11-02T13:55:18.734Z	604	704	704	704	USDT-BTC-BNB	-0.30%
27127	2023-11-02T13:55:43.774Z	1034	1034	632	1034	USDT-DAI-BTC	-0.29%
27128	2023-11-02T13:55:48.783Z	638	638	3141	3141	USDT-BTC-BUSD	-0.30%
27129	2023-11-02T13:56:28.852Z	1191	690	788	1191	USDT-BUSD-DOGE	-0.29%

Figure 20: Snapshot of Sequential Execution

B - Concurrent Execution Segment

	A	B	C	D	E	F	G
29014	2023-11-02T13:44:15.228Z	690	592	589	690	USDT-BTC-BRL	0.23%
29015	2023-11-02T13:44:20.241Z	901	801	702	901	USDT-DAI-BTC	-0.19%
29016	2023-11-02T13:44:30.274Z	634	731	1932	1932	USDT-BNB-BRL	-0.29%
29017	2023-11-02T13:44:55.288Z	638	739	737	739	USDT-BTC-MATIC	-0.29%
29018	2023-11-02T13:45:00.288Z	2136	1035	636	2136	USDT-DAI-BTC	-0.30%
29019	2023-11-02T13:45:05.290Z	635	737	635	737	USDT-BTC-MATIC	-0.28%
29020	2023-11-02T13:45:20.295Z	634	735	637	735	USDT-DOGE-BUSD	-0.30%
29021	2023-11-02T13:45:25.297Z	635	637	635	637	USDT-BTC-MATIC	-0.28%
29022	2023-11-02T13:45:55.342Z	668	768	668	768	USDT-TRX-BTC	-0.30%
29023	2023-11-02T13:46:05.351Z	675	672	673	675	USDT-BNB-BTC	-0.29%
29024	2023-11-02T13:46:50.424Z	627	729	626	729	USDT-BTC-MATIC	-0.30%
29025	2023-11-02T13:47:20.471Z	661	664	663	664	USDT-BTC-BUSD	-0.29%
29026	2023-11-02T13:47:30.488Z	676	673	673	676	USDT-BNB-BTC	-0.29%
29027	2023-11-02T13:48:40.568Z	626	623	623	626	USDT-BUSD-DOGE	-0.30%
29028	2023-11-02T13:49:00.612Z	658	661	661	661	USDT-MATIC-BUSD	-0.30%
29029	2023-11-02T13:49:15.622Z	2162	761	662	2162	USDT-DAI-BTC	-0.29%
29030	2023-11-02T13:49:20.627Z	667	664	664	667	USDT-BNB-BTC	-0.30%
29031	2023-11-02T13:49:35.628Z	657	757	658	757	USDT-DAI-BTC	-0.29%
29032	2023-11-02T13:50:35.671Z	674	674	676	676	USDT-BTC-BNB	-0.28%
29033	2023-11-02T13:50:40.673Z	1076	676	674	1076	USDT-BUSD-BTC	-0.30%
29034	2023-11-02T13:51:15.692Z	1077	677	677	1077	USDT-DAI-BTC	-0.30%
29035	2023-11-02T13:53:20.834Z	663	1561	760	1561	USDT-BUSD-DOGE	-0.29%
29036	2023-11-02T13:53:35.862Z	1181	881	681	1181	USDT-DAI-BTC	-0.30%

Figure 21: Snapshot of Concurrent Execution