Hummingbot
Decentralized market making

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Abstract

Tokenization not only brings the promise of increased efficiency in the conveyance of currently tradable assets, it also has the potential to unlock liquidity for previously non-tradable assets. However, one impediment to fully realizing this state is the general lack of liquidity for all but a limited number of top digital assets trading on centralized exchanges. The growth in the number of cryptocurrency exchanges as well as digital assets has far surpassed the increase in the number of and capabilities of cryptocurrency market makers, leading to liquidity fragmentation and inadequacy across exchanges and assets. Contributing to the lack of liquidity for some trading venues, in particular decentralized exchanges, is the increased technical complexity of transacting through native blockchain protocols as well as a lack of technical standardization. Meanwhile, these inefficiencies also create market trading opportunities for capable traders. With the goal of overcoming these limitations, we introduce Hummingbot, open source software that enables users to create custom, automated trading strategies that can transact on both centralized and decentralized exchanges. Hummingbot's objective is to enable a broader set of users to act as market makers, an activity previously limited to only sophisticated and highly technical market participants, and promote the concept of *decentralized market making*.

Contents

1 BACKGROUND

1.1 Liquidity Is a Scarce Resource

Proponents of tokenization, the process of creating a digital asset transferrable on a public distributed ledger, espouse its ability to unlock the liquidity premium in asset classes such as startups, real estate, and private equity. This is supported by academic research, which has shown that liquidity benefits market participants via efficient price discovery. Liquidity improvement improves the availability of public information about a firm, and improved information will lower the risk premium of the firm, thus decreasing its cost of capital [1].

Yet in practice, tokenization has led to extreme concentration of liquidity. There are thousands of tradeable digital assets and hundreds of exchanges, but liquidity is heavily concentrated in the top assets and venues. The top three digital assets have a combined daily exchange trading volume of $12 billion, 72% of total daily exchange trading volume. Of the more than 2,000 crypto assets listed in CoinMarketCap, 92% have less than $1 million in daily volume [2]. Factoring in over-the-counter trading (OTC) volume between institutions, which deal almost exclusively in the largest digital assets, would likely further increase liquidity concentration.

When the number of markets increases relative to the number of liquidity providers, a power-law distribution for liquidity is the natural equilibrium state. In a hearing on capital markets before the United State House of Representatives in 2011, Eric Noll from Nasdaq spoke about the challenges faced by small-capitalization stocks after the rise of alternative trading systems and dark pools for equities: "The unintended consequences of that market fragmentation have been a lack of liquidity and price discovery in listed securities outside of the top 100 traded names and a disturbing absence of market attention paid to small-growth companies by all market participants, including exchanges [3]."

While tokenization enables assets to trade freely, it does not automatically confer liquidity onto them. In order for the global financial system to fully realize the value of tokenization, there needs to be sufficient actors who are both incentivized and equipped to provide liquidity, especially for the long tail of tokenized assets.

1.2 Market Making in Fiat Markets

Providers of liquidity on financial markets are called *market makers*. Market makers play a fundamental role in asset markets by simultaneously quoting *bid* (offers to buy) and *ask* (offers to sell) prices for assets on an exchange. By quoting prices at which they stand ready to buy and sell assets, they enable price discovery and liquid trading by other market participants. In addition, by quoting prices on different trading venues and arbitraging away inter-market dislocations across different markets, market makers increase overall market efficiency.

In traditional securities markets such as equities, regulatory barriers prevent individuals and small firms from filling the market maker role. On the New York Stock Exchange (NYSE), only member organizations who have been granted approval to act as Designated Market Makers and Supplemental Liquidity Providers are allowed to make markets. Similarly, Nasdaq market makers are required to register with FINRA and apply to be a Nasdaq member firm [4].

In addition, competitive barriers also prevent small participants from acting as market makers. In a practice known as *co-location*, high frequency trading (”HFT”) firms pay exchanges to place servers in close physical proximity to the exchange's own servers, providing lower latency access to data feeds and trade execution. HFT firms have collectively spent massive sums building networks of wireless towers, fiber optic lines and submarine cables designed to provide millisecond-scale time advantages versus other market participants. Furthermore, fiat exchanges like NYSE and Nasdaq charge as much as $22,000 per month for access to market data feeds [5].

Since HFT firms earn profits by performing a high volume of trades, they tend to focus on making markets in large-capitalization stocks. In a 2011 House of Representatives hearing, Joseph Mecane of NYSE Euronext said, “A lot of the spread compression and increased competition that we have seen has been in the very large liquid stocks where you have seen a lot of algorithmic type trading, high-frequency-type trading, which tends to narrow the spread and make it very cheap and efficient and fast for the large-cap stocks to trade. The unfortunate reality is those same trends haven't occurred in the small- and mid-cap part of the market. Those stocks don't have sufficient liquidity for the high-frequency-type automated traders to traffic in those names, and as a result, you have not seen a commensurate level of volume or liquidity or spread compression that you have seen in some of the large-cap names [3].”

1.3 Market Making in Digital Markets

Digital markets remove the regulatory and competitive constraints that impede market making in fiat markets. Individual traders have direct market access to digital asset exchanges, enabling them to provide price quotes and execute trades programmatically using the same APIs as professional firms. Digital asset exchanges also provide market data feeds free of charge.

While certain exchanges provide volume-based fee rebates that favor professional trading firms, they generally do not offer co-location or other features that provide significant competitive advantages to large players at the expense of smaller ones. In addition, since the digital asset exchange landscape is highly competitive with hundreds of active, globally accessible venues, exchanges who introduce anti-competitive features would likely lose business from individual traders and small firms who move their activities to other exchanges.

Yet despite the removal of the regulatory and competitive barriers to market making, there remains relatively few market makers compared to the proliferation of digital assets and exchanges, leading to the extreme concentration in liquidity mentioned earlier. Market makers for digital assets, primarily quantitative hedge funds and trading firms, are in high demand, evidenced by the compensation they receive from both exchanges and issuers.

Most exchanges charge higher commissions for takers (traders who fill existing price quotes) and a lower or zero commission for makers (traders who provide price quotes). Some exchanges also provide rebates to market makers that may exceed their total commissions.

Technical barriers prevent additional entrants from making markets for digital assets. Due to the highly volatile nature of digital asset prices, market makers need to utilize an automated, algorithmic approach in order to stay competitive. Unlike in fiat markets where the Financial Information eXchange (FIX) Protocol provides a standardized message format for electronic trading, digital asset exchange APIs vary in both format and reliability. Market making algorithms need to handle edge cases such as stale data, trade execution lag, and API downtime. Writing robust, reliable market making algorithms that can trade on multiple exchanges requires significant specialized engineering resources.

2 DECENTRALIZED MARKET MAKING

When market making is the exclusive province of large institutions, both fiat and digital markets show that liquidity becomes highly concentrated in the top assets and trading venues. Yet for tokenization to succeed and inject liquidity into formerly illiquid assets, there need to be liquidity providers who are both incentivized and equipped to make markets in a wide range of tokenized assets, not just the top ones.

While direct market access and the absence of competitive barriers like co-location allow for new entrants in digital asset market making, technical barriers remain high. By lowering these technical barriers and introducing new incentive mechanisms, we enable anyone to act as a market maker for digital assets, a new model for liquidity provision that we call *decentralized market making*.

2.1 Rationale

While market making has historically been exclusive to highly specialized professional trading firms, individuals and long-term investors may actually have structural advantages in filling this function for digital assets.

2.1.1 Lower Cost of Capital

Since market makers need to hold inventory for each trading pair and venue on which they provide price quotes, they need to factor in the opportunity cost of that inventory, which may be more profitably utilized in a more profitable market. Moreover, since funds and trading firms are capitalized by external investors, return on capital from market making may need to exceed 20% or greater. In thinly traded markets without the volume to support this return on capital threshold, it may not be economically rational for professional market makers to participate.

In contrast, individuals and long-term investors have lower opportunity costs. Since borrowing and lending markets for digital assets are still nascent, most individuals and long-term investors buy and hold them in wallets or exchanges and do not earn interest or other incremental income from them. For these investors, their return on capital threshold is 0%, and assuming risk neutrality, they should be willing market makers for any market in which they expect a positive return.

2.1.2 Fundamental Conviction

Professional market makers are less likely to have conviction on fundamental value for a digital asset; they generally approach market making from a purely technical perspective. This makes them ill-suited to make markets in illiquid, volatile assets without a lengthy record of trading activity. When prices drop sharply and approach zero, their typical recourse is liquidation.

Individual token holders and long-term investors, however, are more likely to have fundamental conviction. Since their price floor for an digital asset is utility value (in the case of individuals) or investment valuation (in case of investors), they are better equipped to be buyers of last resort and make markets for illiquid, volatile assets.

2.2 Introducing Hummingbot

As a first step toward enabling decentralized market making, we introduce Hummingbot, an open source software client that allows users to create and customize automated, algorithmic trading bots for making markets on both centralized and decentralized digital asset exchanges. Since Hummingbot needs to access sensitive digital asset private keys and exchange API keys to operate automatically, we design it as a user-operated local or hosted client, similar to a cryptocurrency mining node.

2.2.1 Related works

Hummingbot builds upon and extends the work of other open source market making tools for digital assets. These include exchange-specific or asset-specific tools for BitMex [6], MakerDAO's DAI stablecoin [7], and the BitShares decentralized exchange [8].

Furthermore, other open source projects enable automated strategies for market making [9], exchange arbitrage [10], and general algorithmic trading [11] of digital assets.

Hummingbot differs from these other tools in a following areas:

1. **Exchange and asset agnostic**: Hummingbot is designed to make markets across all exchanges and all digital assets

2. **DEX compatibility**: Hummingbot supports market making on decentralized exchanges

3. **Cross exchange market making**: Hummingbot supports a strategy that profits from differences from liquidity between exchanges that offer markets in the same trading pair (see *Strategies* section for more details)

4. **Simpler installation and configuration**: Hummingbot is designed to be installed and used by non-technical users

In addition, smart contract-based automated market makers such as Bancor Network and Uniswap [12] provide liquidity for tokenized assets according to deterministic algorithms. Given the dynamic nature of markets, we believe that a deterministic approach alone may not provide a complete liquidity solution. We plan to integrate these services into Hummingbot as additional channels for users to both source and provide liquidity.

2.2.2 Target Users

Individual Hobbyists

Hummingbot is aimed at cryptocurrency enthusiasts who want to actively participate in strengthening blockchain-based networks while simultaneously earning passive income. Similar to other software clients such as a mining node in proof-of-work blockchains, a staking node in proof-of-stake blockchain, and a validator node in the Cosmos protocol, Hummingbot enables users to perform a specialized service for profit.

Long-Term Fund Investors

In addition, Hummingbot enables crypto hedge funds and other long-term investors to utilize their inventory of digital assets for market making. In addition to providing a new, uncorrelated income stream, market making can have a positive halo effect on an existing investment portfolio since improving liquidity for an asset tends to improve price discovery and lower its risk premium.

For this user segment, we plan to offer services and paid modules that address their specific needs, such as:

- Hosting, deployment, and maintenance
- Integrations with portfolio and execution management systems
- Access to historical order book data
- Custom market making strategies

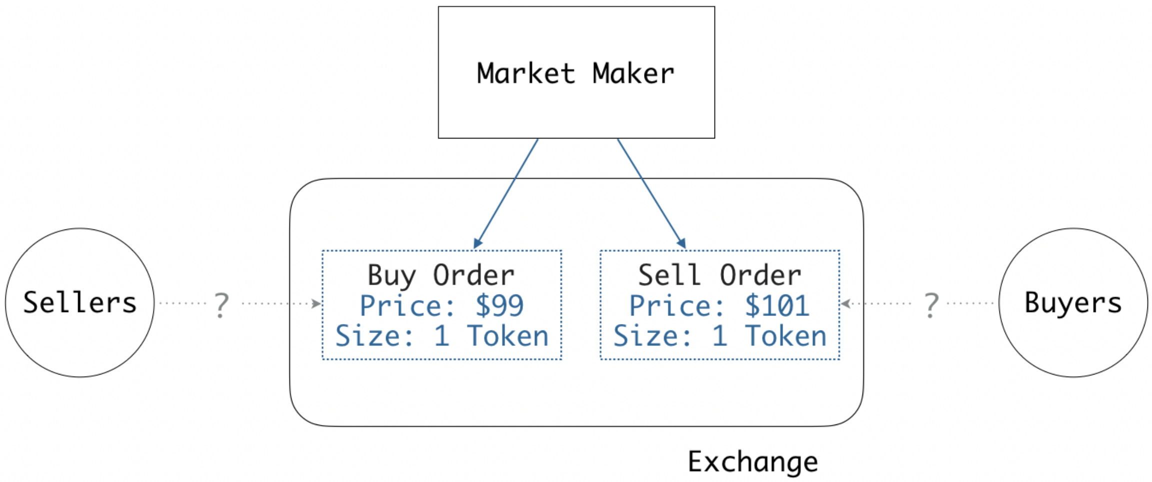
3 STRATEGIES

Hummingbot will enable users to automatically run a set of market making bots based on their custom parameters and strategies. In this section, we discuss the general categories of strategies that Hummingbot helps users define, parametrize, and execute.

3.1 Market making

The basic action performed by a market maker is to quote tradable bid and ask prices on a single trading venue which can be transacted by other market participants at any time (*Figure 1*).

Figure 1: Market maker placing orders for 1 unit of Token



Market makers periodically update these bid and ask prices to reflect factors such as changes in market conditions, trades executed, as well as inventory and resulting levels of risk exposure.

Thus, a market maker encounters a decision problem as described in the Glosten-Milgrom model [13] of dealer markets: because she must set prices in an environment where there exist informed and uninformed traders, the market maker is at an information disadvantage. In addition, a market maker acts as an intermediary between buyers and sellers, whose orders may arrive asynchronously, resulting in fluctuating amounts of inventory and risk exposure. In order to compensate for these risks, a market maker quotes a lower bid price and higher ask price, with the difference in prices referred to as the *bid-ask spread*:

$$\begin{aligned} P_{bid} &= P_{ref} - \delta_{bid} = \text{market maker's price to buy assets}, \\ P_{ask} &= P_{ref} + \delta_{ask} = \text{market maker's price to sell assets}, \\ \textit{bid-ask spread} &= P_{ask} - P_{bid} = \delta_{bid} + \delta_{ask}, \end{aligned}$$

$$\begin{aligned} \text{where } P_{ref} &= \text{reference price}, \\ \delta_{bid} &= \text{spread from reference price to bid price}, \\ \delta_{ask} &= \text{spread from reference price to ask price}. \end{aligned}$$

An example of a market maker *transaction cycle* is:

1. A market maker simultaneously quotes both P_{bid} and P_{ask} for 1 unit of Token A.
2. At some time t_1, a trader fills a market maker's bid order, selling Token A to the market maker. This decreases the market maker's U.S. dollar holdings by P_{bid} and increases his inventory of Token A.
3. A market maker continues to hold the additional inventory of Token A for some unknown period of time.
4. At some later time t_2, a trader fills the market maker's offer order, buying Token A from the market maker. This increases the market maker's holdings of U.S. dollars by P_{ask}[1] and decreases his inventory of Token A.

The market maker therefore assumes incremental inventory risk for an indeterminate period of time, $t_2 - t_1$.

In the example above, the market maker's profit is $P_{ask} - P_{bid} = \textit{bid-ask spread}$[2]. A market maker's economic objective is to maximize the frequency of crossing trades, completing the transaction cycles of buying assets and selling assets (or, conversely, for a market maker with inventory, selling assets and re-buying those assets) in order to capture the bid-ask spread.

Market makers bear risk because:

1. They have to maintain inventory of the quote currency in order to be able to quote ask prices[3], exposing them to negative price movements;
2. Their inventory of the quote currency may increase at any point in time in the event that bid orders are filled;
3. The amount of time required to find an offsetting trade is unknown, during which the value of held inventory may drop, and
4. They are exposed to information disadvantage, since their trade orders may be filled at any time by any trader that may have more information than the market maker.

3.1.1 Inventory Implications for Market Makers

A market maker's current amount of inventory and target level of exposure have implications on its bias for assuming more or less risk; naturally, the willingness of a market maker

[1]Assuming no change in prices between t_1 and t_2

[2]Ibid

[3]In a base case, where shorting assets is not available to the market maker.

managing for a target level of exposure is inversely proportional to its level of holdings. The resulting bias can be expressed in the market maker's quote through price (or spread), order size, or both:

$$(q_{current} > q_{target}) \rightarrow [(\delta_{bid} > \delta_{ask} \vee s_{bid} < s_{ask})], \tag{1a}$$
$$(q_{current} < q_{target}) \rightarrow [(\delta_{bid} < \delta_{ask} \vee s_{bid} > s_{ask})], \tag{1b}$$

$$\begin{aligned} \text{where } s_{bid} &= \text{bid order size}, \\ s_{ask} &= \text{ask order size}, \\ q_{current} &= \text{current level of inventory}, \\ q_{target} &= \text{target level of exposure}. \end{aligned}$$

For example, a risk averse market maker (as in the case of equation (1a), where a market maker's current holdings exceed target holdings) skews the parameters of its market orders in order to decrease the probability and/or magnitude of acquiring more inventory relative to selling inventory.

3.1.2 Implementation

Market making is a complex optimization problem [14], in which all information known at a given point in time (including historical data) is used to generate market orders that maximize expected returns of the strategy. The basic algorithm for a market maker is to (1) establish a reference price for the asset, and then (2) set bid and ask prices, as well as respective order sizes, for orders to be placed on the exchange.

There are multiple approaches for accomplishing both steps, and strategies must be customized to take into account characteristics of the asset as well as the market maker.

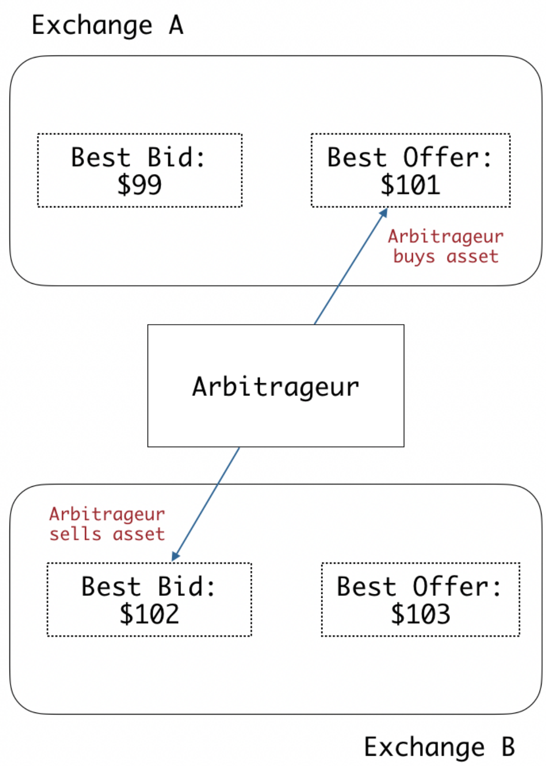
Market Maker Parameters

Asset price volatility	Target asset exposure
Risk bias	Risk exposure limits
Current amount of inventory	Order duration
Margin thresholds	Quote frequency

3.2 Arbitrage

Arbitrage trading is the strategy of capturing risk-free[4] profits by simultaneously buying an asset at a lower price and selling that same asset at a higher price (*Figure 2*). From time to time, market dislocations may present such opportunities for a number of reasons.

Figure 2: Arbitrageur simultaneously buys and sells an asset on different exchanges to capture $1 risk-free profit



Market Fragmentation in Digital Asset Markets

The relatively nascent digital asset markets makes it susceptible to pricing dislocations due to significant market fragmentation. There are multiple exchanges with different pockets of users: some users may have access to some exchanges, while others do not. In addition, new exchanges continue to be created regularly.

[4]Arbitrage trading aims to eliminate market risk or price risk. However, there may be some residual risks due to the logistics of executing or settling trades, for example risks inherent in the transfer of assets between exchanges, or the risk of an order being filled or being canceled prior to the arbitrageur completing that trade.

Some of the broader factors resulting in fragmented cryptocurrency markets include:

- **Centralized exchanges versus decentralized exchanges**:
  - Certain traders may not be able to trade on decentralized exchanges (e.g. due to regulatory requirements or risk tolerance/reliability concerns) or they may not have the technical expertise to transact in the native technologies of the decentralized exchanges, which currently are generally more complex than transacting on centralized exchanges.
  - Price quotes and trade execution on decentralized exchanges may be subject to delays arising from dependencies on the underlying blockchain protocols.
- **Geographically ring-fenced exchanges**: exchanges in one country may not be able to open accounts for non-nationals of that country. Multiple exchanges exist that are geographically dispersed, with limited or no overlap in user bases.
- **Exchange Proliferation**: There currently exist over 200 cryptocurrency exchanges globally[15] with different user and asset bases, and the ability to move assets from one exchange to another (even for a user with accounts on each exchange) may require complex, time-consuming processes and be subject to fees. Since exchanges may have silo-ed user bases, each may have different supply and demand dynamics making them prone to dislocations.

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Information Asymmetry

There may be ephemeral opportunities arising from a delay in information spreading across multiple markets, time zones, or exchanges. For example, if an account places a large buy order in one exchange which drives prices higher on that exchange, a quick-acting trader may be able to accumulate those assets at lower prices on other exchanges which have not seen that buy order, and then sell those assets at the higher prices on the original exchange. This may be observed across different geographies.

Structural Fragmentation

In some cases, there may be persisting reasons for market dislocations arising from structural or regulatory reasons. One example of this is is a persisting material pricing discrepancy in the Bitcoin market between Korea and the U.S. In fact, this led to a market "crash" as CoinMarketCap removed the elevated Korean exchange prices from its calculations[16]. Korean cryptocurrency prices exceeded those on U.S. exchanges due to high internal demand for cryptocurrencies. However, this persisted because of the challenge for Korean nationals to open accounts in other countries as well as currency controls limiting the amount of cash sent overseas. In this example, a trader with access to both markets could buy cryptocurrencies in the U.S. and sell them in Korea and capture risk-free, arbitrage profits.

Trader / "Fat Finger" Errors

The decentralized and retail nature of cryptocurrencies coupled with the idiosyncratic pricing conventions and number systems used by cryptocurrencies gives rise to the possibility of trade entry errors. In addition, the increasing adoption and use of algorithmic strategies and programmatic, automated trading systems further adds to the likelihood of trade entry errors. Such large errors have been witnessed in long-established, traditional markets such as the stock markets (e.g. 2010 Flash Crash [17]). This creates the potential for arbitrage opportunities resulting from pricing errors, as a trader accepting that order may be able to offset the trade at a "normalized" price.

Challenges for Arbitrage Trading

Arbitrage trading is a very attractive trading strategy due to its guarantee of risk-free profit. However, identifying arbitrage opportunities is challenging since (1) they should not exist, as the market naturally works to eliminate such inefficiencies, (2) they are unpredictable, non-recurring, and may be small in size, (3) typically short-lived, and (4) there is high competition to identify and capture such mispricings while there can only be one winner.

Being able to consistently capture arbitrage profits depends on some form of advantage which is difficult for other market participants to replicate. Examples of such advantages may be high speed data connections between different exchanges or locations (such as "high-frequency traders" in the traditional financial markets), access to cryptocurrency exchange accounts across multiple countries, or superior technologies for constantly monitoring and detecting pricing dislocations across multiple exchanges coupled with the ability to reliably respond and execute quickly. Unlike traditional financial markets such as the stock market, the cryptocurrency market continuously trades without a defined market open or close. Searching for arbitrage opportunities requires constant monitoring.

3.2.1 Implementation

Hummingbot arbitrage strategies will monitor multiple exchanges for any price dislocations and transact whenever a profitable trading opportunity arises. When using an arbitrage strategy, Hummingbot will act a market taker, filling the best available trade orders on different exchanges.

Hummingbot will enable the execution of multiple strategies which will be released in stages, such as:

1. ***Basic arbitrage strategies***: singe trading pair on two exchanges
2. ***Multiple exchange strategy***: increase likelihood of identifying arbitrage opportunities by monitoring multiple exchanges (more than two)
3. ***Multiple trading pair strategies / triangular arbitrage***: a common strategy in foreign exchange markets, using more than a single trading pair for capturing arbitrage. Increased complexity and additional trading pairs increase the likelihood of the occurrence of a pricing dislocation.

Some of the technologies that will be part of Hummingbot's arbitrage strategy development include:

- **Integrations with different exchanges**: retrieving order book and price data, sending trade instructions, and (optional) rebalancing / transfers of assets between exchanges.
- **Exchange order book analysis**: study multiple exchanges in order to try to identify highest potential for arbitrage opportunities.

Critical to the success of the arbitrage strategy will be the ability to reliably detect opportunities and respond quickly.

3.3 Cross-Exchange Market Making

Cross-exchange market making combines elements from both arbitrage trading and basic market making in order to profit from differences in liquidity between trading pairs from two (or more) different exchanges.

In cross-exchange market making, a market maker trades on two different exchanges and uses the best available bid and asks (*Figure 3*) available on one exchange ("Exchange A", typically, a larger, highly active and liquid exchange) in order to make markets on another exchange ("Exchange B", a smaller, less actively-traded exchange). Any time the market maker's order is filled on Exchange B, the market maker can immediately offset this trade by filling the corresponding order on Exchange A.

The market maker enters orders on Exchange B with a margin δ_{ask} relative to the best prices on Exchange A (*Figure 4*). For example, the best offer price on Exchange A is $101;

Figure 3: Asset is quoted on Exchange A

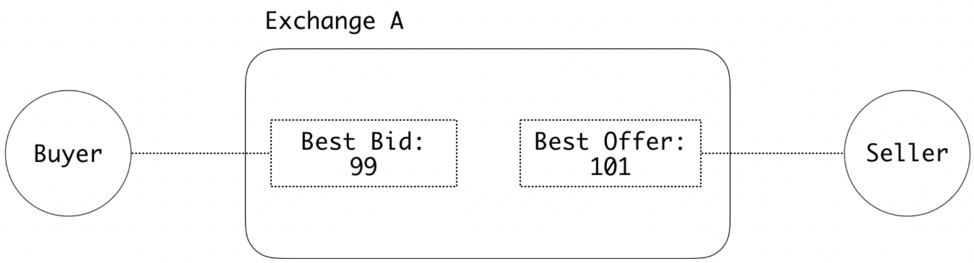
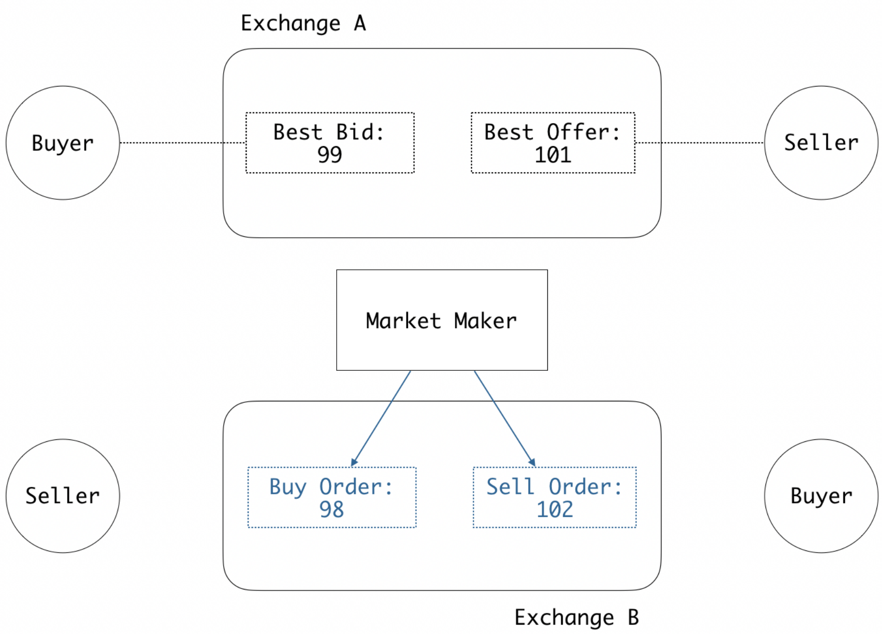


Figure 4: Market maker enters orders on Exchange B



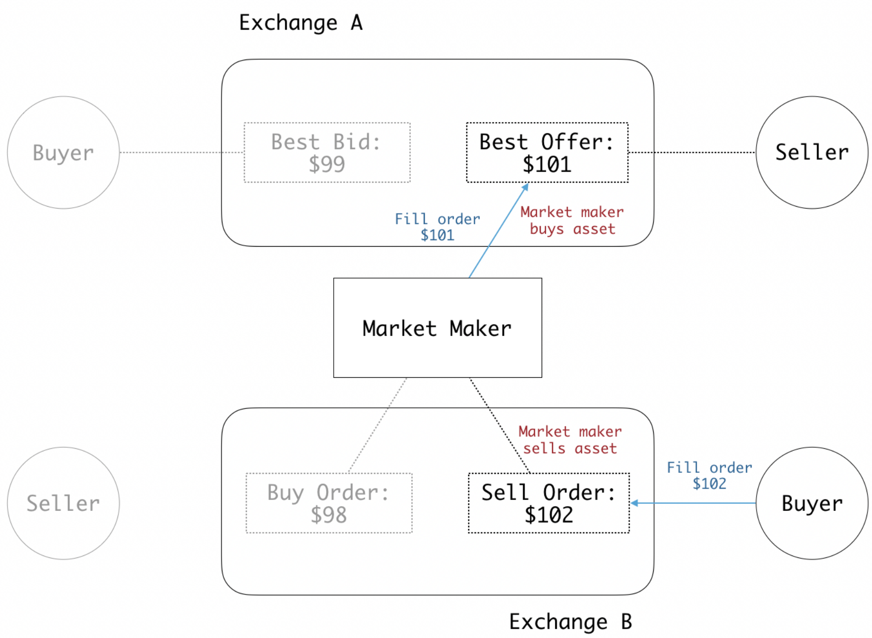
the market maker can quote an offer of \$101 + δ_{ask} on Exchange B, which in the example is \$102.

When a trader fills the sell order on Exchange B, the market maker instantly offsets the trade by buying the asset on Exchange A (*Figure 5*). Since the market maker sold the asset at \$102 on Exchange B and was able to simultaneously buy the asset from Exchange A for a price of \$101, the market maker realizes a risk-less profit of \$1.

Use Cases

Cross-exchange market making allows market makers to take a more active role in pursuing

Figure 5: Buyer on Exchange B fills Market Maker Sell Order, Market Maker Simultaneously Buys the Asset on Exchange A



arbitrage opportunities. Whereas in pure arbitrage trading arbitrageurs search for, or wait for, pricing dislocations, cross-exchange market making allows a market maker to actively create the potential for capturing price differentials.

The strategy also enables market makers to "clone liquidity"[5] from one exchange to another exchange, particularly in the case of replicating liquidity from a larger, more liquid exchange to smaller, less liquid exchanges. One example of this would be bridging liquidity from centralized exchanges to decentralized exchanges, where the user base is materially smaller.

3.3.1 Cross-Exchange Market Making Implementation

Inventory Equilibrium Model

The previous example explains cross-exchange market making in an efficient markets environment where transferring assets across exchanges is instant and friction-less. In practice, inter-exchange transfer of assets may be inefficient, time-consuming, incur fees, and may contribute to the existence of pricing dislocations in the first place. For example, transferring of any blockchain-based asset may require the transfer instruction being mined in a

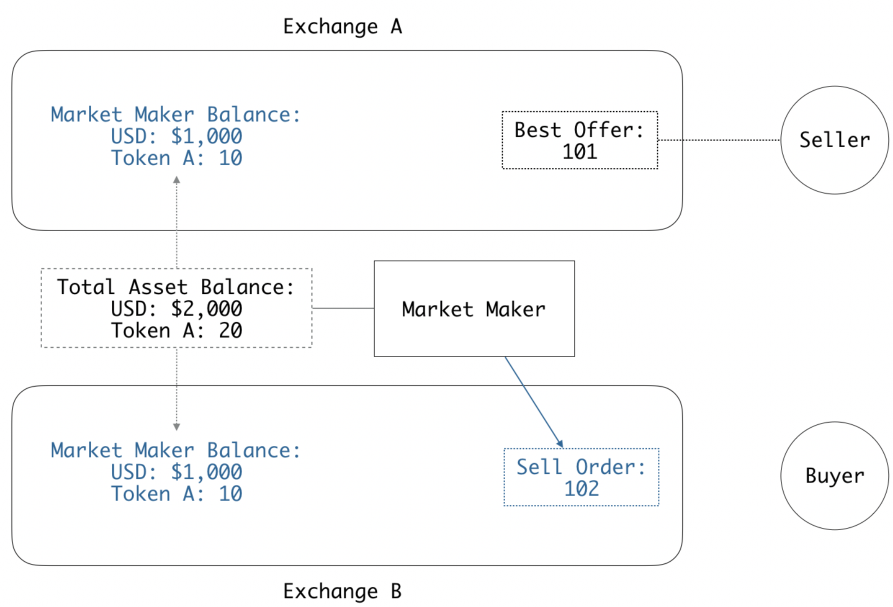
[5]Cloning liquidity may also be referred to as *remarketing*.

blockchain transaction and confirmed between exchanges. Since pricing dislocations may exist only momentarily, any profitable opportunity may easily dissipate in the amount of time it would take to transfer the assets and complete both sides of the transaction.

One way to address this inefficiency is for a market maker to maintain inventories on multiple exchanges, allowing for the market maker to act immediately when presented with a profitable trading opportunity. As in the example above, the sell order on Exchange A and the buy order on Exchange B occur in the same manner as previously described, allowing the market maker to complete offsetting trades. However, in a cross-exchange, inventory equilibrium model that takes into account inter-exchange asset transfer inefficiency, the market maker would maintain balances of both U.S. dollars (the assumed quote currency of the example) and the asset on both exchanges. In executing the above transaction, no assets are immediately transferred between Exchange A and Exchange B.

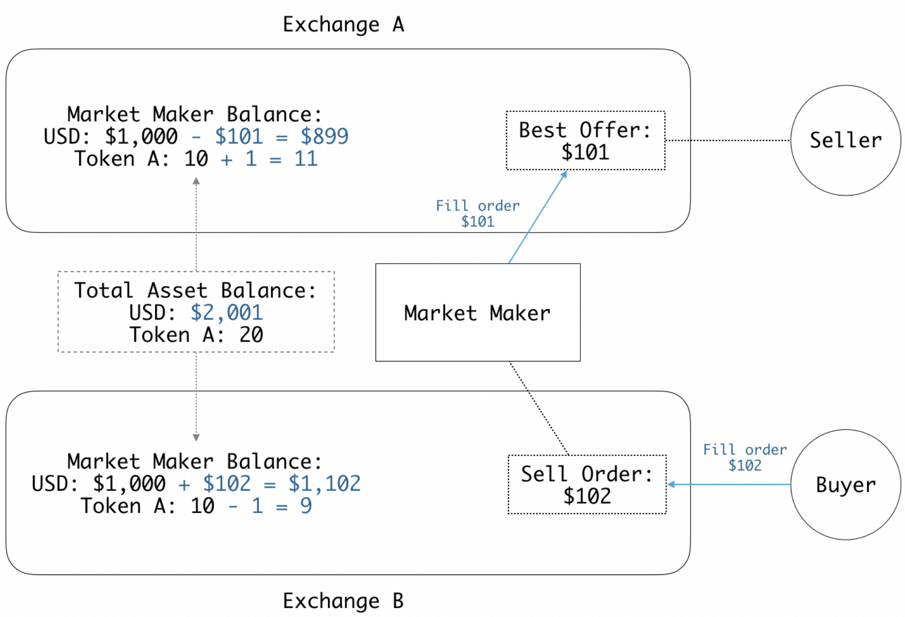
In the example shown in *Figure 6*, the market maker has a total inventory of USD 2,000 and 20 Token A assets, equally distributed between Exchange A and Exchange B.

Figure 6: Market maker maintains an inventory on both exchanges



When a buyer takes the market maker's sell order on Exchange B for 1 unit of Token A, the market maker simultaneously buys 1 unit of Token A on Exchange A. There is no transfer of assets between exchanges, resulting in a change in the cross-exchange distribution of the market maker's assets. Following the trade, the market maker's overall exposure has remained unchanged: the market maker still has an aggregate balance of 20 units of Token A, however, now with 11 units on Exchange A and 9 units on Exchange B. Meanwhile, the market maker's total cash balance has increased by the $1 profit captured, with a new total cash balance of $2,001, with $899 and $1,102 on Exchange A and B, respectively (*Figure 7*).

Figure 7: A buyer on Exchange B takes the market maker's sell order; market maker simultaneously buys the asset on Exchange A



3.3.2 Inventory Risk and Implication for Strategy Applicability

A fundamental difference between basic market making on a single exchange and cross-exchange market making is the requirement to maintain some amount of inventory for an indeterminate amount of time, whereas as previously discussed, basic market making generally aims to minimize the amount of inventory and the duration of holdings. While the potential to capture incremental arbitrage trading profits increases the expected value of a portfolio, the market maker does retain market and price risk.

The ideal user for such a strategy would be a market maker that has a fundamental investment thesis for the asset and is a long-term holder of the asset. Deploying a cross-exchange market making strategy can provide a market maker with incremental, additive returns without a fundamental change in risk profile as compared to a passive, buy-and-hold strategy.

4 THE HUMMINGBOT CLIENT

By encapsulating market making algorithms and a trade execution engine in an open-source application available to non-technical users, Hummingbot enables a much wider range of individuals and companies to potentially earn income from running market maker nodes that provide liquidity to crypto-asset pairs that trade on various exchanges.

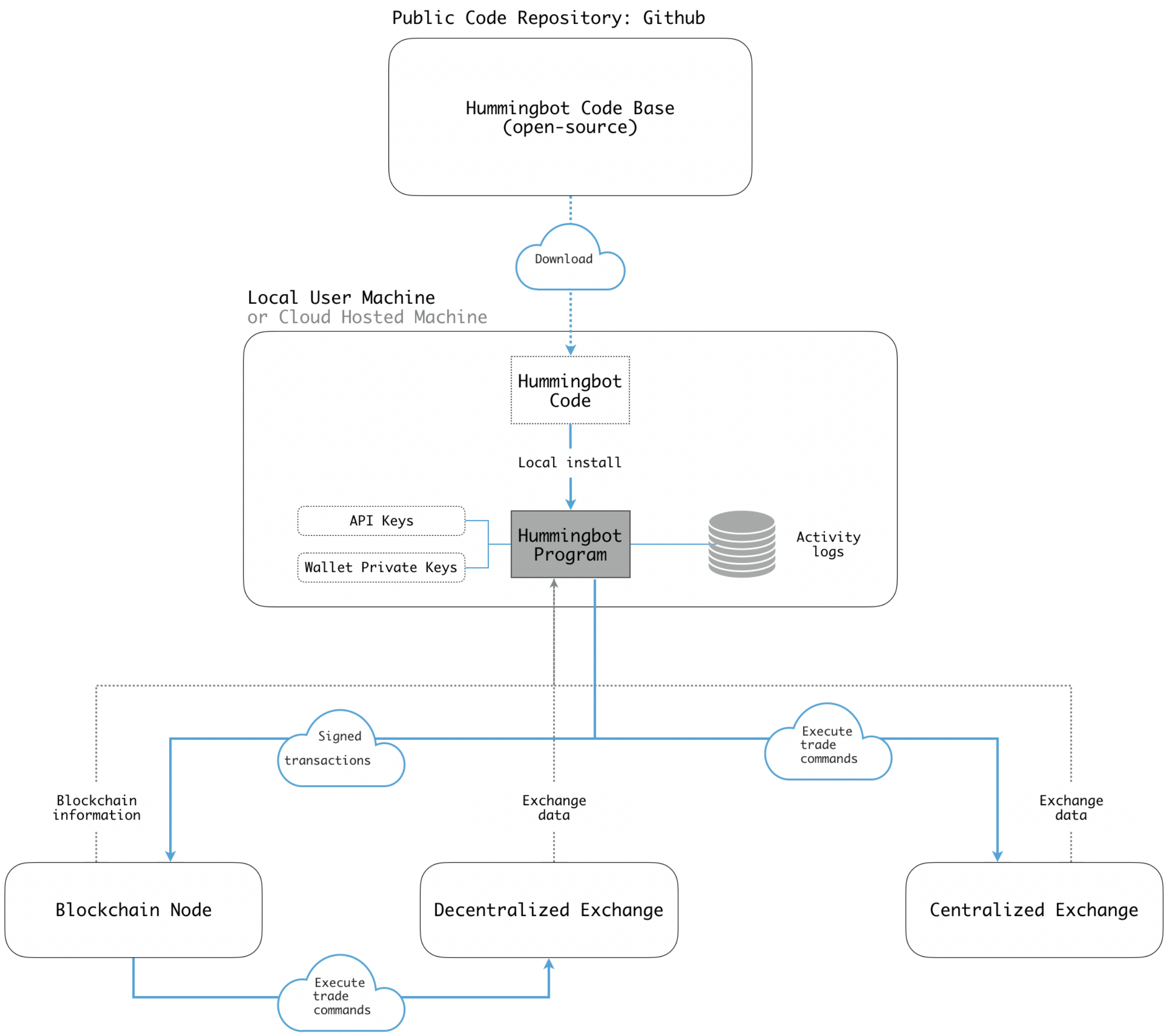
Hummingbot will effectively be a trading engine to execute transactions with the parameters provided by users, abstracting some the technical complexities of transacting with centralized and decentralized exchanges, each with their own non-standardized technical specifications. Hummingbot will facilitate trade execution and interaction with different exchanges, performing actions such as price and order book retrieval, submission of trade instructions, and, if specified by the user, handle asset transfers for functions such as re-balancing across different exchange accounts.

4.1 Architecture

The Hummingbot architecture and operation are similar to the operation of open-source, blockchain protocol nodes (*Figure 8*).

1. ***Bot installation***: users download the code from a public, open-source code repository and install the program locally, either on their local machine or on a cloud-hosted remote server.
2. ***Program execution***: users execute the Hummingbot program either through command line commands or a graphical user interface (GUI).
3. ***Private information*** (such as wallet private keys and exchange API keys): are encrypted and stored locally on a user's machine.
4. ***Bot activity and transaction logs***: stored on a local database.
5. ***Data feeds***: the program connects to blockchains, decentralized exchange APIs, and centralized exchange APIs to retrieve data, such as market prices and order book data, as well as user specific data such as asset balances, existing orders and status.
6. ***Centralized exchange commands***: the bot uses locally stored API keys to create API requests for interacting with centralized exchanges for the retrieval of information as well as for sending user instructions.
7. ***Decentralized exchange commands***: the bot uses the locally stored wallet key to sign transactions which are then sent to a blockchain node for execution.

Figure 8: Hummingbot Architecture



4.1.1 Reliability Engineering

Similar to the cryptocurrency market, its associated infrastructure is relatively nascent. In recent months, there have been hundreds of new exchanges created, with limited track records and deploying new, relatively untested technologies. A primary engineering task in the development of Hummingbot is in making it reliable and capable of handling extrinsic failures, some arising from idiosyncratic risks of the cryptocurrency market.

Risk Mitigation for Interexchange Trading When trading across different exchanges, it is critical to coordinate transactions across different exchanges, particularly when they are related transactions, such as the offsetting transactions used in arbitrage trading and cross-exchange market making. This is further complicated the use of decentralized exchanges, where there is increased potential of delays in the execution of transactions (e.g. waiting for block confirmations or block reorganizations). An example of the risk of coordination is one leg of traded being executed on one exchange (Exchange B), while in the interim, the offsetting hedging transaction on another exchange (Exchange A) on which that trade was based has gone away (e.g. trade was filled by a third party or orders were withdrawn).

Risk mitigation:

- Increase spread buffer for transactions
- Analysis on speed of transactions on exchanges
- Order book depth analysis to optimize trade parameters and account for contingencies (e.g. taking next best orders)
- Sourcing offsetting transactions from multiple exchanges

Exchange Reliability

Unlike the more established exchanges of financial markets, cryptocurrency exchanges have, in their short history, experienced service disruptions. Even some of the major centralized cryptocurrency exchanges have experienced service outages, some for as long as several days [18]. For decentralized exchanges, one additional risk is the occurrence of blockchain congestion [19], while technology changes (e.g. the change in API specifications) can disrupt any software depending on those services.

Risk mitigation:

- Constant monitoring and reporting of exchange status
- Flexibility to relocate trading to different exchanges
- Information redundancy (e.g. multiple sources for asset price feeds)

4.1.2 Strategy Implementation

Phase 1

The initial release of Hummingbot will focus on the cross-exchange market making strategy between a centralized exchange and a decentralized exchange.

Ongoing development will add additional features:

- Support for additional centralized exchanges
- Support for additional decentralized exchanges
- Centralized to centralized exchange market making
- Stand-alone arbitrage trading or overlay to market making strategy (e.g. execute taker transactions whenever an trading opportunity exists)
- Support for multiple exchanges (more than two)

Phase 2

Pure market making strategies for making markets for a single asset on a single exchange.

Phase 3

Provide the capabilities for customized user strategies.

- Initial focus on cross-exchange market making for decentralized exchanges
- Add other strategies over time
- Custom strategies: users can also write their own strategies

4.1.3 Rebalancing

When employing a cross-exchange market making strategy, it is increasingly likely with the passage of time that an imbalance in the direction of trading flows will accumulate. In the example above, if higher price levels persist on Exchange B, there will come some point in time where either the market maker's holdings of Token A on Exchange B and US Dollars on Exchange A will be depleted, or both. This creates the need to rebalance and redistribute assets across exchanges.

Rebalancing can be automated and incorporated into the trading bot strategy, by specifying minimum asset balance thresholds that trigger a rebalancing. Rebalancing is carried out by the bot initiating asset transfers between exchanges.

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