Currency Engineering

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*The fundamental results presented in this paper are a re-exposition and extension of a series of unpublished papers by the physicist Henri D. Rathgeber (1908-1995). See endnotes for details.

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1 Introduction

We show how the process by which people drive markets to a sustained and stable equilibrium of aggregate supply and aggregate demand is constrained and destabilized by technical properties of the currency used. We identify the major technical problems with legacy currencies and present a design for an significantly improved currency that is highly likely to maintain a sustained and stable state with aggregate supply in equality with aggregate demand and full-employment.

Around 1777 David Hume observed, despite theoretical considerations to the contrary, that properties of a nation's currency had observable affects on the state of the economy,

> If we consider any one kingdom by itself, it is evident, that the greater or less plenty of money is of no consequence; since the prices of commodities are always proportioned to the plenty of money, and a crown in Harry VII.'s time served the same purpose as a pound does at present ... It is indeed evident, that money is nothing but the representation of labour and commodities, and serves only as a method of rating or estimating them. Where coin is in greater plenty; as a greater quantity of it is required to represent the same quantity of goods; it can have no effect, either good or bad, taking a nation within itself; any more than it would make an alteration on a merchant's books, if, instead of the Arabian method of notation, which requires few characters, he should make use of the Roman, which requires a great many ... **But notwithstanding this conclusion**, which must be allowed just, it is certain, that, since the discovery of the mines in America, industry has encreased in all the nations of Europe, except in the possessors of those mines; and this may justly be ascribed, amongst other reasons, to the encrease of gold and silver. Accordingly we find, that, in every kingdom, into which money begins to flow in greater abundance than formerly, every thing takes a new face: labour and industry gain life; the merchant becomes more enterprising, the manufacturer more diligent and skilful, and even the farmer follows his plough with greater alacrity and attention. This is not easily to be accounted for, if we consider only the influence which a greater abundance of coin has in the kingdom itself, by heightening the price of commodities, and obliging every one to pay a greater number of these little yellow or white pieces for every thing he purchases.

Hume's considerations suggest that any effective economic model requires an understanding of both how people interact with others, changing their individual economic agreements in a way that pushes markets toward equilibrium of supply and demand, but also an understanding of the role of money as an essential tool is those market transactions.

Considering the economic process in the absence of currency, the process of supply and demand as we understand it, infers a macro-economic equilibrium where aggregate demand and aggregate supply are in equllity, i.e. that if we aggregate excess supply and demand across markets, they should average out to close to zero.

[more details here]

However, contrary to Figure **??** which implies full-employment Figure 1 shows a vastly differing results.

Figure 1: Inflation Rate vs. Unemployment Data

[asymmetry diagram].

Positive rates of unemployment are so consistent across all countries and throughout the decades of recorded economic history, to such an extent that unemployment appears as solid as physical law.

Economic theorists have been seeking a solution to this problem for many years without success. Considering that any currency mechanism is absent from this model of supply and demand, despite Hume's observations suggest currencies have significant effects, it seems reasonable to find a way to include currency in our model. This leads to the question of what methods should be used to analyze the properties of currency. The fundamental insight that we present is that because currency is a digital system, the way to approach its analysis is roughly analogous to the way we approach the analysis and design of other digital systems (the internet being an interesting example), i.e. that we should approach the analysis of currency as an engineering problem, and in particular the engineering and control of dynamic systems.

Economic theory approaches economic problems similarly to the way medicine treats the human body, by applying relatively small changes, such as medicine, in response to various pathologies. Destructuring and rebuilding biological systems is impossible. Importantly however, the control system for economies, the currency, can indeed be destructured and rebuilt from first principles. Thus we take a different approach, viewing currency more like a robotics problem, something that can be built from the bottom up.

1.1 Transactions

The mechanism of accounts holding a monetary value that can be transfered to other accounts mirrors the physical world or transfer of ownership of a limited supply of paper money or similar means. This mechanism can be used by people in many ways. We categorize the main uses into different kinds of transactions. This is important because a digital currency can apply a layer of abstraction and control on the different kinds of transactions in such a way as to achieve desirable global conditions. So while money as a transfer of a single value is flexible, it also limits the currency's ability to control transactions to achieve desirable goals. Digital currencies allow for the possibility of stricter control at the transaction level in order to achieve global conditions that a simple token exchange currency cannot achieve.

Historical experience is a good guide to the main uses which people use money for, and these can be categorized into various types of transactions. The simplest and most fundamental transaction are exchange transactions as shown in figure 2.

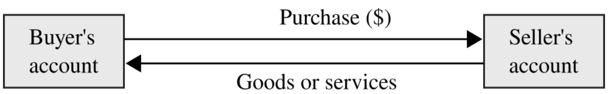

Figure 2: Exchange Transaction

We can consider exchange transactions as occuring at a point in time, where goods or services are exchanged for currency. Another common type of transaction we will call a time transaction,

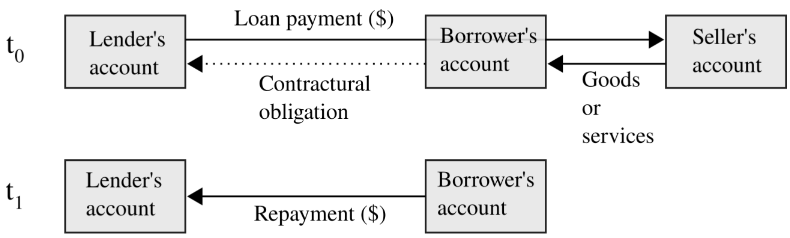

Figure 3: Time Transaction

where at time t_0 money is borrowed and used to make an exchange transaction of currency in exchange for goods and service. At a later time t_1, the principal and interest is repaid to the lender. The third transaction category we call contract transactions. Contract transactions are characterized by a transfer of money in return for a change in owner of contractural obligations.

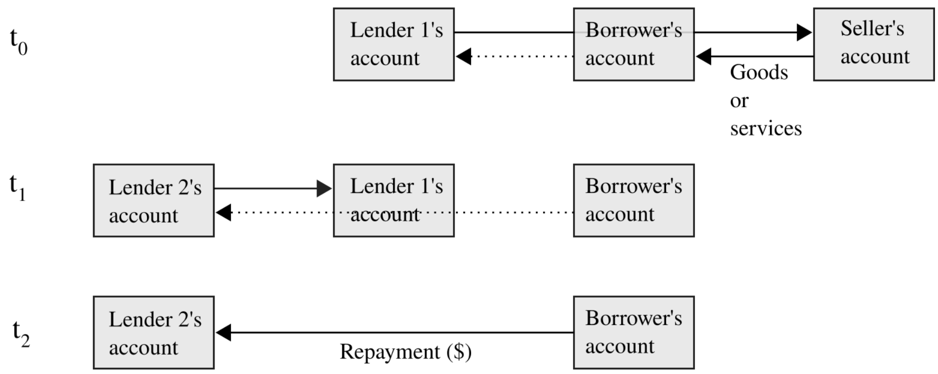

Figure 4: Contract Transactions

Contractural transactions and variations on them can become complex. Transactions are not limited to these categories. We will examine some other transaction categories later in the paper.

1.2 Feedback Regulators

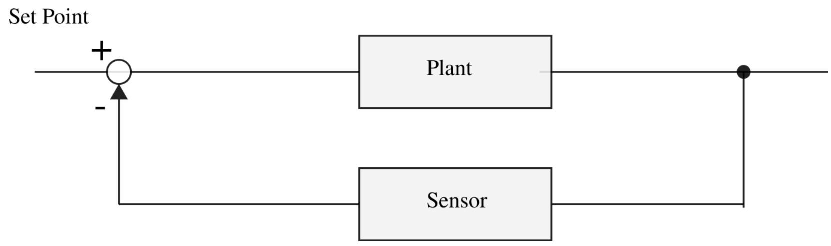

Figure 5: Economic Feedback Schema

A general control system schema with a single control variable can be represented as

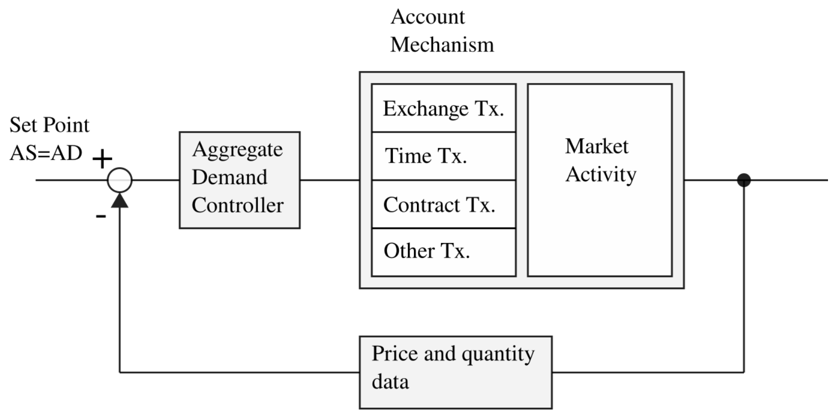

Figure 6: Economic Feedback Schema

A set of possible transactions provides an interface to the currency's accounts. In designing a digital currency, we have considerably more control over the way in which accounts are used, compared to a paper currency where everyone is free to exchange units of currency. The currency also consists of a also a feedback mechanism, controlled algorithmically or through a monetary authority, to regulate aggregate demand. The process by which people drive markets to an equilibrium of aggregate supply and aggregate demand occurs in the Market Activity box. This process which we think of as the central driver of market activity, is internal to currency feedback mechanism. As we will show, the design of the currency constrains can prevent this process from reaching equilibrium and we required further regulatory mechanisms built into the currency.

1.3 Results

Engineering methods are applied to the the currency mechanism not the behaviour of people. The only assumptions made about people's decision-making processes and the basic tenets of supply and demand interaction, that people drive markets to equilibrium (and this assumption itself is confirmed when we test the theory against data (6)). In the remainder of the paper by start with the the currency control system as shown in Figure 6, and step-by-step take each transaction category, introduce it into the model and apply engineering analytical methods. As a result of this process we find the following requirements,

1. Aggregate demand must be continuously increasing at a rate sufficient to compensate for errors. Without this requirement the currency constrains the transaction possibility space of markets, preventing people from driving markets to macro-economic equilibrium.

2. All units written into contracts must be independent of the price level. Without this condition a positive feedback instability can result in runaway behaviour under increases in the inflation rate.

3. Contract transactions must be prevented. Without this condition contract transactions can result in runaway behaviour in prices, difficulties in controlling an overly complex system. Preventing contract transactions allows for a currency design with precise control over aggregate demand.

1.4 Implementation

There appear to be effective design solutions to meet these requirements.

In the absence of contract transactions a unique global value, a *Demand Index* D_x can be used by a central monetary authority or by algorithm to precisely control aggregate demand. Accounts store a base value and payments are in purchase value, demoninated in a unit (such as $) that is a product of the base value and the demand index. In general the base value is hidden from users and accounts appear as purchasing value.

The *Price Index* P_x is regularly published, and all legal contracts must be written in a unit of account of constant purchasing power. This setup has been used in Chile for several decades for almost all contracts and has proven practical even when being used with a paper currency. With thus unit of account in place, the aggregate demand of a currency can be directly controlled and variable rates of inflation without risk of runaway behaviour.

A digital currency can be designed to distinguish between exchange transactions and time transactions.

Exchange transactions would require both the buyer and lender to record the quantity of goods and services purchase. This record could also be used by sellers and buyers to record agreements, but the use of cryptographic methods to prevent such purchase data being available to others except those directly involved in the transaction is required. This mechanism would also ensure that accurate price and quantity data could be recorded for the calculation of a Price Index.

Time transactions would require the same conditions as an exchange transaction, but also that the repayment schedule is determined at the time of the initial loan payment, and that the recipient of the loan repayment is the same account from which the load payment was made.

This would generally prevent the use of contract transactions which require that the recipient of repayment changes. It is still possible for people to make informal contracts, and to obfuscate the initial loan payment and repayments as exchange transactions, by recording a false good or service. This however, would forgo both parties any right to legal process in the case of a dispute, because the transactions are clearly marked as an exchange, with no further contractural obligations.

2 Introduction to Dynamic Systems and Control

The purpose of this section is to present the field of dynamic systems and control to a reader who is not familiar with the topic. Our goal is to demonstrate the huge technological significance of control system design, and to make clear that the methods used in this paper are all very much standard practice. Other than the original insight of the application of control system design to the economic problem, the analysis is nothing new, albeit presented in a somewhat unusual way so as to provide a crash-course in the intuitions and basic analytical method while avoiding formal mathematical methods.

2.1 Brief History of Mechanic Feedback Mechanisms

TODO: Huygens

TODO: Watt

TODO: Maxwell

Prior to the Wright brother's first flight in December 1903, Orville and Wilbur Wright believed that the most fundamental problems they needed to solve were control problems. In September 1901 Wilbur Wright's first public presentation on the feasibility of heavier-than-air flight stated that "When this one feature [control] has been worked out the age of flying machines will have arrived, for all other difficulties are of minor importance."[49]

2.2 PID Controllers

TODO

2.3 Feedback Systems and the Internet

TODO

3 Exchange Transactions

3.1 An Exchange Transaction Only Model

We will start with a model simplified from Figure 6. that includes only exchange transactions.

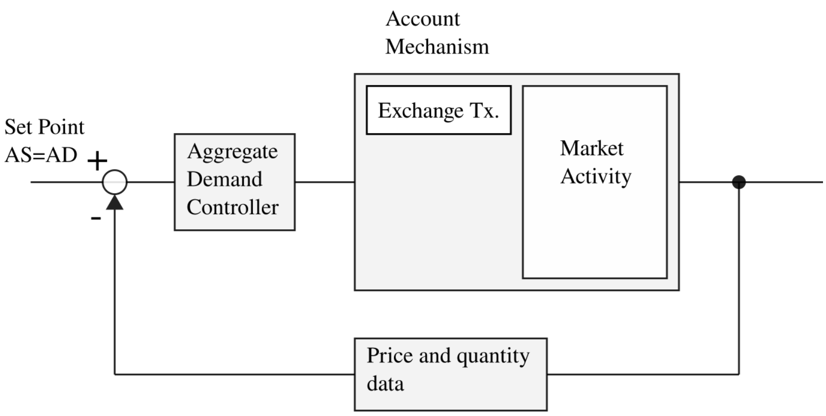

Figure 7: Exchange Only Feedback Schema

3.2 Price and Quantity

An exchange transactions can be characterized by a payment. We will use the unit "dollar" for payments. In exchange for a payments is a quantity of goods or services of a certain goods category. We denote the quantity with a unit specific to the goods category. The price of the transaction is the ratio of payment to quantity and the unit is dollars per unit of the goods category. These variables relate directly to properties of transactions which indicate the state change in a set of accounts. They are precise and measurable quantities, so we treat them differently to measures of economic measures which try to handle some notion of human good. We denote f_i are the sum of payments for a given goods category i over a period of time The unit for any i is "dollars". We denote the quantity of that goods category transacted in exchange for these payments q_i. The unit can be different for each i. The average price of each goods category is

$$p_i = \frac{f_i}{q_i}$$

We can sum f_i for all transactions in a given period.

$$F = \sum_i f_i \tag{1}$$

As will be shown later, the aggregate value we are interested in is an accurate measure of the price level such that a person own x dollars now has the same purchasing power at any time in the future. To make this more precise we need to define purchasing power.

Suppose we have an economy at time $t = 0$ that makes transactions

$$(q_1, \ldots, q_n)$$

where there are n goods categories, and the unit of quantity for each goods category may be different. We write the units corresponding to each goods category as

$$([q_1], \ldots, [q_n])$$

The average price for all transactions within a good category can be written

$$(p_1, \ldots, p_n)$$

with the corresponding units

$$\left(\frac{\$}{[q_1]}, \ldots, \frac{\$}{[q_n]}\right)$$

We need to specify this more precisely. The quantity and proportion of different goods transacted using a currency changes over time. We use the notion of purchasing power to construct a measure to handle this. We can image an "abstract person" who we feed dollars, and make random selections of goods and services *per dollar*. So we want to find numbers P and P' such that the following equation holds

$$\frac{1}{P}\left[\frac{p_1 q_1}{F} + \cdots + \frac{p_n q_n}{F}\right] = \frac{1}{P'}\left[\frac{p'_1 q'_1}{F'} + \cdots + \frac{p'_n q'_n}{F'}\right] \tag{2}$$

Variables without a dash refer to time period $t = 0$ while variables with a dash refer to time period $t = 1$. This is a dynamic equation, i.e. it defines relations relations across time. We'll proceed by constructing some measures of aggregate quantity and aggregate price level, and then check that these measure do conform to our requirement in equation (2). First, we want to construct a measure of price level P as a function of $p_1, \ldots p_n$, and a measure of aggregate quanitity Q as a function of $q_1, \ldots q_n$. These are static variables, dependent only on other variables that are measured at the same time. But the problem is that we can't aggregate some Q from $q_1, \ldots q_n$ because the units for each goods category can be different. This also means we can't aggregate some P from $p_q, \ldots q_n$ because the units for p_i are

$$\left[\frac{\$}{i}\right]$$

where i, the units the goods category is measured in, can be different. The way we get around this problem is to constrain the units we are working in. As an aside, it is interesting to note that David Hume's argument heavily relies on the price units. What we are doing here is extending Hume's notion to both price units and quantity units.

If at any period of time the following quantities of goods are transacted

$$\overline{Q} = (q_1, \ldots, q_n)$$

then we choose any set of units $\dot{Q} = c\overline{Q}$. In other words we choose a "basket of goods" that is an exact multiple of the actual goods transacted at any time. This quantity has the units

$$[B] = ([cq_1] \ldots [cq_n]) \tag{3}$$

and now we define P as the quantity of baskets B that make up total transactions F, i.e.

$$F = PQ$$

The units of P are $\left[\frac{\$}{B}\right]$. Very much like f_i is independent of the scalar value of a goods category unit we choose, F in independent of the scalar value of the basket of goods we choose, given that equation (3) holds. We now look at the dynamics. We have one degree of freedom remaining, i.e. our choice of c. At any time period, we can choose an arbitrary c but our goal is to be able to compare aggregate price across time. The problem we face is that the relative proportions and prices p_i and q_i can change across time.

The problem becomes trivial if the proportions do not change, we just use the same unit for all time periods. To account for changes in relative proportions of prices and quantities, which directly map into changes in our basket of goods, we need to relative change in the makeup of the basket of goods from aggregate changes. We do this by taking setting c and c' such that the average change in quantities of goods in our basket remain constant, weighted by relative proportion of spending $\frac{f_i}{F}$.

$$\frac{c'}{c} = \frac{\varepsilon[B]}{\varepsilon[B']} \tag{4}$$

where the expected value ε is weighted by $\frac{f_i}{F}$. This can be written

$$\frac{1}{c}\left[\frac{f_1}{F}q_1 + \ldots + \frac{f_n}{F}q_n\right] = \frac{1}{c'}\left[\frac{f_1'}{F'}q_1' + \ldots + \frac{f_n}{F'}q_n'\right]$$

Increasing c by a factor, reduces Q by this factor, and increases P by this factor.

3.3 Concrete Example

To make this clearer, lets look at a concrete example. Lets say there are two goods (maybe apples and bananas) are transacted in a digital currency a and b.

In the first period the transactions are

2 apples	$2
4 bananas	$1

and in the second period the transactions are

3 apples	$2
4 bananas	$1

In the first time period we construct a basket with units $[0.5(2\text{apples}, 4\text{bananas})]$.

3.4 Control of Price Level

Before examining exchange transactions, we will briefly consider the feedback control mechanism. Indexation is an important method for controlling distributed systems like a currency. An index is a single value that is utilized by multiple components. An example of indexation in digital currencies is Bitcoin's method for regulating the rate of production of blocks by Bitcoin miners. In this case the indexation is algorithmic rather than controlled by a central authority. TODO

Another example of indexation is

The simplest way to control the price level in a digital currency is to use indexation.

TODO

The feedback control loop does not work, however, in legacy currencies because the core currency doesn't account for all money. Most money in legacy currencies is banking money, termed M1, M2 and M3. Under these conditions, money authorities must use alternative methods to try and induce financial institutions to increase the amount of banking money mainly through changing the interest rate at which the money authority lends core currency to those financial institutions. At times this method has been effective at controlling the price level, at other times less so. The process lacks precision and has a long time-lag, making its use as the main mechanism for controlling economic conditions problematic. Its effectiveness is also determined by financial institution's ability and willingness to respond to decreases or increases in the monetary authority's core lending rate in a way the maps to increases or decreases in aggregate demand.

3.5 Market Symmetry

4 Exchange Transactions and Errors

4.1 Information Theory

5 Time Transactions

5.1 Including Time Transactions in Our Model

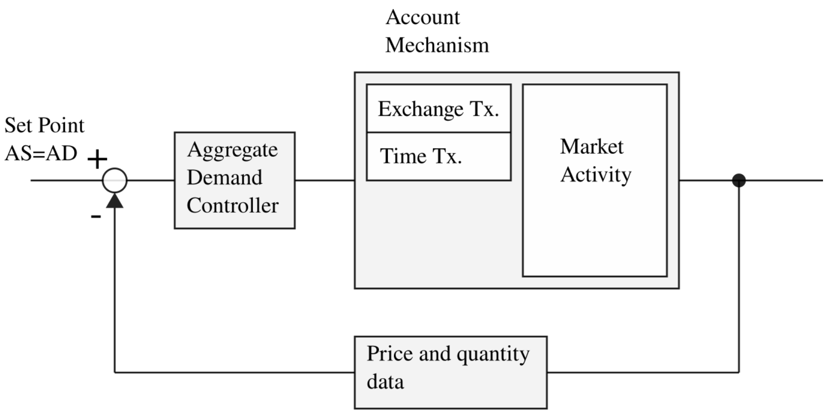

Figure 8: Exchange and Time Transaction Feedback Schema

5.2 Interaction of Time Transactions and Exchange Transactions

There is a positive feedback interaction between exchange transactions and time transactions that is driven by increases in the inflation rate.

In his 1896 work *Appreciation and Interest* Irving Fisher examines an adjustment that economic participants must make to nominal interest rates if they are to maintain real interest rates at a certain fixed rate, under inflationary conditions. We consider a simple example.

This is a process which in addition together with the effect of an error rate on market equilibrium accounts for most of the effects of currency on market stability equilibrium and stability.

6 Data

7 Contract Transactions

8 External Transactions

9 Other Transactions

10 Implementation

Abstraction Layer over Accounts

To implement a currency design that does not constrain

we need to reconsider the interaction between the micro-level, the economic participants and owners of accounts, and the macro-level requirements.

The design strategy we take is to define the macro-level requirements and then to search for ways to control the currency so that the currency is likely to map out to those macro-level requirements.

We specify the macro-level requirements as

1. Sustained stability.
2. Macro-level equilibriation.

Simple accounts that hold a number with some control of the aggregate value in all accounts is the digital equivalent of paper money. This design is insufficiently controlled to achieve our two macro-level requirements.

To achieve these outcomes we apply a abstraction layer over these accounts. This abstraction layer does the following:

Exchange Transactions

1. Present to the user a value that is the product of the user's base account value and an single, global value that we call the demand index (D_x). This product is the value that users generally see and is the value in which price agreements

are made. This value gradually changes as the demand index changes, appearing to users much as a bank account that has gradual increases as an interest rate is applied to it. As such, it presents no usability difficulties to the user.

3. All exchange transactions must be associated with a quantity and a goods or service category. An exchange transaction is only valid if both the seller and buyer confirm the same goods or service category. This serves three purposes.

a. It asserts that the transaction is an exchange transaction, and as such, has no associated contract with it beyond the current delivery of the goods or service. By doing this it confirms that there are no future legal commitments to any future repayment. This is required to limit the use of exchange transactions for the purpose of some other transaction category.

b. The data can be used, with necessary software mechanism to ensure the privacy of the data, to accurately calculate the price index.

c. It serves as a record for the seller and buyer to resolve any disputes, i.e. it acts as a receipt or record of agreement.

Beyond the seller and buyer entering the same goods and service category, it is easy for seller and buyer to collude and provide incorrect information.

4. There are intermediate accounts. These are required because all exchange transactions must be associated

TODO

Time Transactions

2. Values that set future payments, in particular for repayments on time transactions, are denominated in a root value and the product of the price index (P_x). In this way, the purchasing power of that value remains absolutely constant, and as such there it present any possibility of inflation feedback. All repayments on time transactions must be defined at the time the money is borrowed and designated as a time transaction.

Contract Transactions

Contract transactions are prevented by the requirement that borrowers must make repayments to the same party that initially lent the money. There are possible ways that users could subvert these requirements which we discuss in a later section.

External Transactions

The provision of an exchange transaction mechanism will be deferred. The possibility of providing exchange transaction functionality with external currencies depends on the design of external currencies, in particular the accuracy of their price index, and their control over contract transactions. If we consider external transactions between two currencies of the kind we are presenting in this paper, then an external exchange rate fixed to the relative price index of the two currencies, and restricting transactions to exchange transactions by requiring the recording of goods or service cateogry and quantity may be a suitable design. This kind of system would require a pair of special aggregate accounts specifically for external transactions to pair up inflow and outflow. In this system, the pairing of inflow and outflow would halt if either account became empty. Another possibility would be to implement a floating exchange rate. The potential difficulty with this design is that it is relatively easy for users to use exchange accounts in lieu or time or contract transactions, and so it may be possible for users to engage in high-frequency capital interactions across the external boundary despite the disincentive of having no legal resort on repayment failure.

Usability

The controls we plan to implement will have minimal impact on any user who intends to use the currency for exchange or time transactions. There is an additional requirement for both seller and buyer to agree on a transaction and to record goods category. Indexed units of account have been used in Chile for a number of decades without significant usability problems, and the use of indexed units of account in a digital currency could potentially further simplify their use.

One important exception, however, are restrictions on the types of repayment schedules for time transactions. If repayment schedules are overly flexible, the repayments could possibly be used, given people's ingenuity in using financial mechanisms to enrich themselves, as a substitute for contract transactions. The extent to which this would happen in practice is unknown, and so starting with relatively strict controls and relaxing restrictions with experience is probably a reasonable approach.

Using One Transaction Category in Lieu of Another

The are various methods that users may potentially use to one category of transaction of another. The most serious risk is that users find ways to make contract transactions. The main barrier to preventing this is to ensure that repayments can only be made to the initial lender's account. The second barrier is to ensure that there is no legal protection to protect creditors from debtor's failure to make "repayments". These barriers should be sufficient on the condition that there are no significant economic incentives for engaging in such activity. In general such users will choose to use other currencies, rather than a currency with these barriers.

11 Conclusion

We summarize the theoretical components according to the level of confidence in the results.

The error effect and Fisher lines

This property is determined by physical properties and the inferences made from these rules are sufficiently precise and measurable to be subject to falisification.

Aggregate equilibrium

The property is an aggregate of people's behaviour that has been observed over long-periods or time with great consistency and is a plausible outcome of people's general incentives. Our model remains robust even if we relax this assumption to a large degree. Almost all fields of economic research are predicated implicitly or otherwise on the idea that this condition must be modified heavily to explain real-world conditions, and therefore require significant re-appraisal given that these effects are better explained as a property of currency design.

Inflation feedback and financial bubbles and crashes

These processes are best explained as positive feedbacks that, while their degree and timing cannot be reasonable determined quanititatively with precision, if unchecked will have clear consequences and these consequences have consistently observed. These positive feedback processes are fundamentally uncontrollable with possible rapid changes that we cannot easily regulate. A successful control system will strongly limit the impact of positive feedback processes.

Market driven changes in aggregate quantities and prices

We cannot expect to be able to predict theses changes, but the rate of change is not sufficiently fast that it cannot be controlled or adjusted for through feedback regulation.

We hope that this paper can lead to new directions in research. In all new engineering endeavours, theory and practice diverge. We can take advantage of the relative easy of building digital currencies to specific design specifications to make currency engineering into an experimental science. Given the theoretical foundations presented in this paper there is a reasonable high chance that we can design and build currencies that will not prevent markets from reaching equilibrium, that that a stable equilibrium can be maintained indefinitely in response to changing conditions.

11.1 Endnotes

According to Rathgeber's notes, the error effect was discovered in 1974. Rathgeber's papers glossed over some matters that caused considerable confusion and doubt about the value of his work. I have tried to make explicit those sources of ambiguity. Rathgeber discusses the need to separate out the "functions of money". This was a source of confusion and lack of precision, which I tried to deal with using the notion of transactions as a way to delineate the different functions of money. Rathgeber did not make a clear distinction between a currency as a technical property as compared to the market behaviour of people, but the notion was implicit in his work. This was also a source a confusion, because people, quite reasonably, object to the application of engineering method directly to social interaction. Making explicit the difference between markets and currency hopefully clear that engineering method is applied to currencies, not social interaction. Rathgeber was working in the context of a single, national, centralized currency. I have extended the application of his ideas to digital currencies. At the time he wrote his private papers, he had access only to Australian inflation and unemployment data. I have extended this to data available up to the time of publication.

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