Currency Engineering

Eric Findlay*

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*The fundamental results presented in this paper are a re-exposition and extension of a series of unpublished papers by the physicist Henri D. Rathgeber (1908-1995).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

Draft only

Contents

1 Introduction

Economic participants drive markets towards equilibrium. This process, however, is contrained by the technical properties of the currency used. This paper describes these technical properties and shows how, by correctly isolating and controlling previously coupled components, effective control of currency can be achieved that is highly likely to lead to sustained, stable, aggregate economic equilibrium with full-employment. Around 1741 David Hume [7] observed that real economic conditions were affected by increases in money supply, which he noted was contrary to the notion that increases in the price, as a unit of measurement, should be independent of the real factors,

> "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 economic participants interact in the market but also an understanding of the role of money in those market transactions. The standard economic supply and demand model, independent of money, infers a macro-economic equilibrium where aggregate demand and aggregate supply are in equality, or equivalently, that aggregate excess supply and demand across markets should average out to close to zero. Contrary to this expectation, all countries experience a sustained state of unemployment and excess aggregate supply as shown in Figure 1.

Figure 1: Inflation Rate vs. Unemployment Rate for 30 Countries

Given that money is absent from this model of supply and demand and that Hume's observations suggest money has 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. Because currency is in essence a system much like other digital systems, such as the internet, it should be approached as an engineering problem, and more specifically as a problem of 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. In general a currency is a set of accounts, each holding a number that can be transfered to other accounts, but a more concrete formulation of how economic participants *use* the currency is required. A currency can be further specified, beyond just a set of accounts for transferring money, to a set of accounts on which certain well defined transaction types are applied. The most common transactions can be categorized into exchange transactions, time transactions, contract transactions and external transactions.

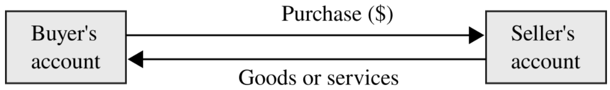

Figure 2: Exchange Transaction

An exchange transaction (Figure 2.) is a payment in return goods and services that occurs at one point in time.

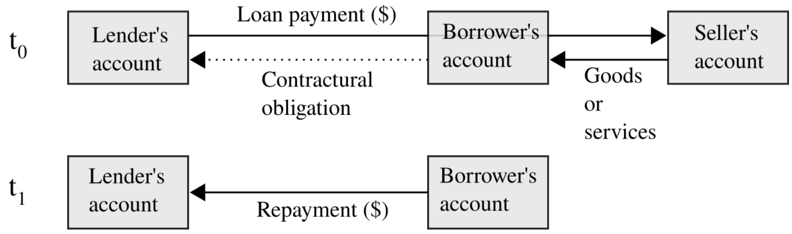

Figure 3: Time Transaction

A time transaction (Figure 3.) extends an exchange transaction and involves the lending of currency at t_0. This money is then used by the borrower for an exchange transaction and a contractural obligation is set up between the lender and the borrower. At time t_1 the principal and interest is repaid to the lender.

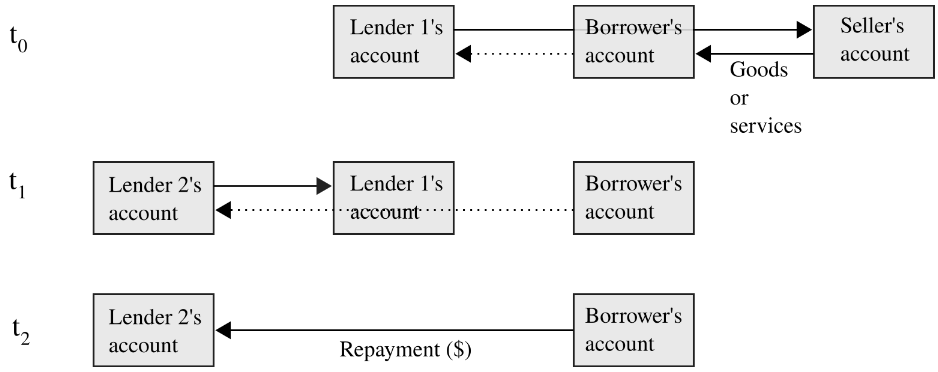

Figure 4: Contract Transactions

A contract transaction (Figure 4.) extends a time transaction and involves payment in exchange for a change in the status or ownership of a contractural obligation. At time $t = 1$ Lender 1 sells the contract to Lender 2. In Section 8. external transactions are also examined.

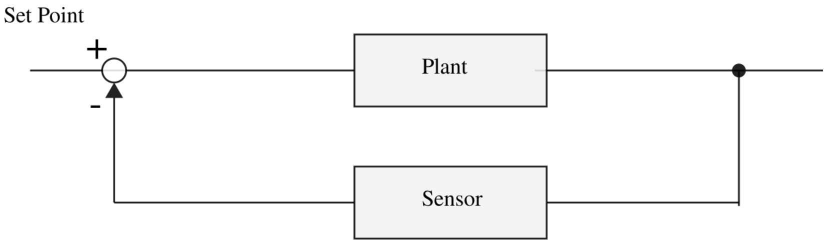

Figure 5: Feedback Regulator Schema

Feedback regulators (Figure 5.) are mechanical devices that regulate dynamic processes. They are self-adjusting mechanisms that work to achieve some desired conditions in the plant by taking measurements from the plant and feeding back the deviation between the measured values and the desired set point back into the plant. Figure 6. shows an economy modelled as a feedback regulator. The plant is a currency, represented as a set of accounts and transactions, and the economic participants who interact through markets using the currency to make transactions.

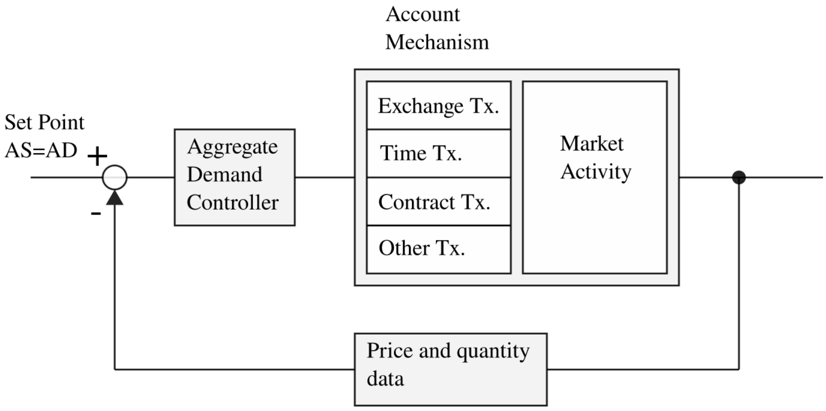

Figure 6: Economic Feedback Schema

Engineering method is applied to the the currency mechanism not the behaviour of people. The only assumption about the behaviour of economic participants is that they drive markets to equilibrium. Our general approach is to take a pared-down version of Figure 6. and step-by-step introduce each transaction type into the model, and then apply normal engineering analytical methods, examining the interaction between transaction types. We find that

1. Aggregate demand must be continuously increasing at a rate sufficient to compensate for errors. Without this requirement the currency constrains the space of possible transactions, preventing people from driving markets to aggregate 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 and interest rate effects on time transaction. Preventing contract transactions also allows for a currency design with precise control over aggregate demand.

A currency that implements these properties is highly likely to result in a economy with sustained, stable, aggregate equilibrium and full-employment.

2 Introduction to Dynamic Systems and Control

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.

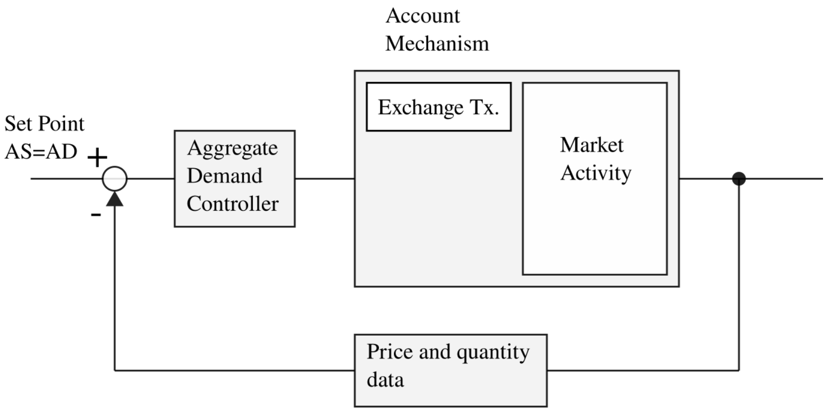

Figure 7: Exchange Only Feedback Schema

3.2 Price and Quantity

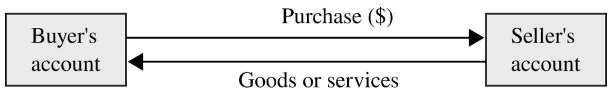

Figure 8: Exchange Transaction

Exchange transactions can be quantified as a payment p denominated in dollars in exchange for quantity q denominated in units specific to that good or service. We want to construct some aggregate variables from p and q. The term *goods category* to used to refer to a particular kind of good or service as this term more closely reflects the idea that the categories can be redefined at various levels of specificity or generality. Using a discrete time model, for each time period we will sum all the quantities of a given goods category i so that we have a set of q_is, and collect these into a vector $\overline{Q}$. We'll let N be the total number of different goods categories.

$$\overline{Q} = (q_1, \ldots, q_n) \tag{1}$$

The units for each q_i are in general different. Units are denoted by enclosing in square brackets. The units corresponding to each q_i are

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

The average price p_i can be calculated by dividing total spending on goods category i by q_i and collecting them into a vector $\overline{P}$.

$$\overline{P} = (p_1, \ldots, p_n) \tag{2}$$

The corresponding units for p_i are

$$\left(\left[\frac{\$}{p_1}\right], \ldots, \left[\frac{\$}{p_n}\right]\right)$$

We cannot sum either these prices or quantities because they can have different units. But each payment $p_i q_i$ can be summed because its unit using dimensional analysis is

$$\left[\frac{\$}{q_i}\right][q_i] = [\$]$$

so we will let total payments F, denoted in dollars, be

$$F = p_i q_i + \ldots + p_n q_n$$

What do we require of an aggregate measure of the price level? As will become clear later in the paper (5.3) we require a measure of the price level P that can be used to accurately index purchasing power of a given dollar value across time. To make this more precise consider Alice who, when she receives a dollar, purchases goods randomly selected in such a way that in the limit, after many purchases, the distribution of her purchases is in proportion to total transactions $\overline{Q}$ at that time. Suppose the price level at $t = 0$ is P_0 and the price level at $t = 1$ is P_1. We want a measure of price level such that if Alice spends 1 dollar at $t = 0$ and P_1/P_0 dollars at $t = 1$, then her expected value, $\overline{\varepsilon}_1$, of her purchases as a proportion of $\overline{Q}_1$ should be equal to the expected value, $\overline{\varepsilon}_0$, of her purchases as a proportion of $\overline{Q}_0$. In other words, we want

$$\frac{P_0 \overline{\varepsilon}_0}{\overline{Q}_0} = \frac{P_1 \overline{\varepsilon}_1}{\overline{Q}_1} \tag{3}$$

We will now build a measure of price from equations (2) and (1) and later check that it agrees with equation (3). The vector $\overline{Q}$ represents a collection of values, but we want to construct a single value that is a aggregate of these values. The problem is that each of these values may have different units. We can construct units that such as "one apple and two oranges" but this limits to what we can measure in these units. We can measure "two apples and four oranges" but we cannot measure "two apples and two oranges". If we consider only a single period of time that has $\overline{Q}$ transactions, then we can express this value in any unit of the form

$$([\gamma q_1], \ldots [\gamma q_n]) \tag{4}$$

for any number γ. So in fact there is not just one, but a set of feasible units in which to express $\overline{Q}$. We refer to any one of these set of units as a "basket of goods". Given that we select one of these sets of units, we can then express $\overline{Q}$ as some number Q, where the units given by equation (4) with a specific γ. The units of Q is this basket of goods. Now we can set the price level as the payment for this basket of goods. This value P is in units \$ per basket. And

$$F = PQ \tag{5}$$

The units used depends on the $\overline{Q}$ at a point in time. If the proportion of q_i changes we would have to use a different unit, and so cannot make comparisons across time. We can solve this problem by making use of our last degree of freedom to further constraining our units. We do set by setting the rule that the proportion of γ_1 to γ_0 is equal to the ratio of trade-weighted averages at times $t = 1$ and $t = 0$.

$$\frac{\gamma_1}{\gamma_0} = \frac{\varepsilon([q_1], \ldots, [q_n])}{\varepsilon([q_1'], \ldots, [q_n'])} \tag{6}$$

where

$$\gamma = [q_1]\frac{f_1}{F} + \cdots + [q_n]\frac{f_n}{F}$$

Now, because γ depends only the average of the units in the baskets of goods, the distribution of q_i around this average becomes irrelevant. This means that *however* $\overline{Q}$ changes, whatever its distribution, the relation $F = PQ$ is exact.

This section has involved various manipulations of units, most critically the ratio of dollar payments to a quantity of some good or service of a collection of different quantities of goods and services. Throughout the paper we will see that questions of units are important. Section 4. will show that the price unit must change over time. In Section 5. we show that the price unit written into contracts must be constant over time. To isolate these different units and construct a control system that has sufficient degrees of freedom required for control, the use of indices is useful.

TODO

3.3 Aggregate Demand, Aggregate Supply and Agreements

From equation (5)

$$\frac{\Delta F}{F} = \frac{\Delta P}{P} + \frac{\Delta Q}{Q}$$

Denoting the rate of change of the price level as the inflation rate I and the rate of Q as the growth rate G then

$$\frac{\Delta F}{F} = I + G \tag{7}$$

Aggregate demand and aggregate demand are a set of transactions

$$\sum_{i=1}^{n} p_i q_i \tag{8}$$

Aggregate supply, AS, is the set of transactions that people will agree to sell if aggregate demand is available. Aggregate demand and aggregate supply are neither well-defined or knowable quantities as they depend on what decisions people have made in their heads. We can only measure outomes of these variables such as F. The unemployment rate is a good measure of excess aggregate supply. We are interested in aggregate supply and demand only to the extent that we can control them. We may be able to control aggregate demand by changing the money supply. Historical experience indicates that at some times control is effective, and at other times control is less effective. The effectiveness of this control depends on the ability to control money supply, and the relationship between money supply and aggregate demand. We assume that an increase in money supply will cause an increase in aggregate demand. We want to be able to control aggregate demand through a feedback regulator. That means that this relationship needs only to be sufficiently strong that it responds to a feedback controller. This feedback controller may be a monetary authority or an algorithm. Later in the paper we'll examine ways to improve this control mechanism. AD and AS we can derive a set of agreements, which are the common transactions in aggregate demand and supply are is the minimum of these two values (denominated in \$), and it is assumed that agreements maps directly to transactions.

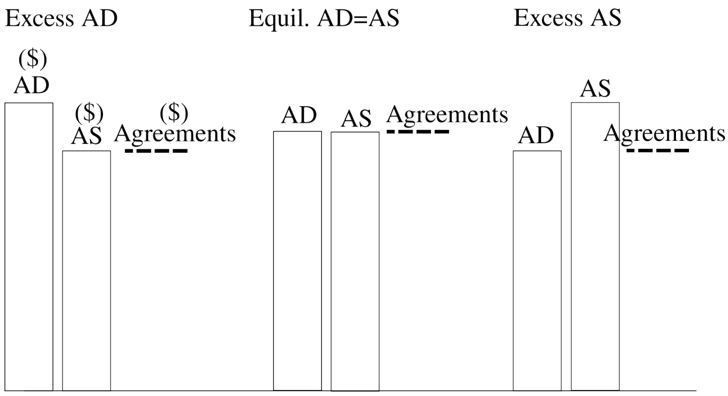

Figure 9: Agreements as a function of aggregate supply and demand

Agreements occur when both sellers and buyers want to transact and so agreements are the minimum of aggregate supply and aggregate demand as shown in Figure 9.

3.4 Market Symmetry

We assume that in aggregate economic participants drive prices and quantities in markets to an equilibrium where $AD = AS$. This assumption is in general contrary to the economic research program which searches for causes in deviations of fact from theory, as encapsulated by Hume's problem, in the behaviour of market participants. One of the clearest deviations of fact from the theory of supply and demand is the question of symmetry. The supply and demand model is symmetrical in that there is no difference between markets being driven away from or to equilibrium as a result of excess demand or markets being drive away from or to equilibrium as a result of excess supply,

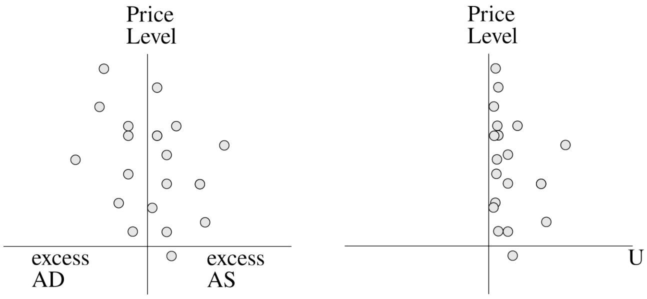

Figure 10: Symmetric Market Model

The right hand side of Figure 10 is a diagrammatic representation of what the outcome of the symmetric market model should look like in measurements of the unemployment rates. Any measurement that represent excess aggregate demand will be mapped to an unemployment rate of zero or close to zero. Half the data-points should therefore sit close to an unemployment rate of zero. This model is inconsistent with many decades of unemployment data.

4 Exchange Transactions and Errors

4.1 Information Theory

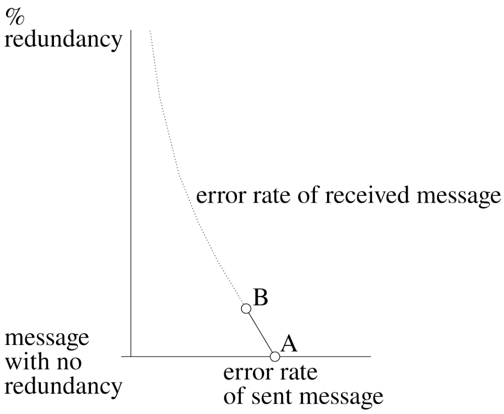

Figure 11: Intuition about Error Rates

Intuitively we might think about how adding redundancy to a message might change the error rate as in Figure 11. The original message with a certain error rate and no redundancy is represented by point A. If we add some redundancy to the error message we might be able to reduce the error rate of the received message to B. It seems that the problem is that for each piece of redundancy we add to the message, we introduce more errors, and so as we increase redundancy we would get decreasing returns on improved error rate. Claude Shannon proved mathematically that this intuition is incorrect, and that there exists a method of adding redundancy to our message such that if we add a H rate of redundancy we can remove all errors from the message. The correct bound on the possible error rate is show in Figure 4.2.

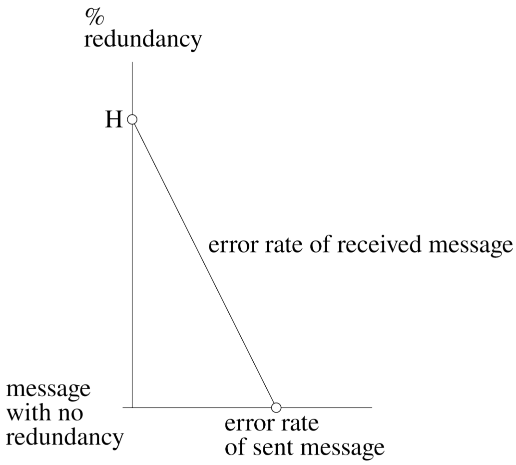

Figure 12: Shannon's Theorem of Noisy Channels

The value H indicates the extra length required of a message so as to compensate for all messages. It is determined by the probabilistic properties of the sent messages. We look into this in more details in **??**.

4.2 Aggregate Supply and Demand

In Section **??** we presented a simple dynamic model of aggregate supply and demand. For any engineering system we must handle the effects of errors or noise on the system. In this section we will look at the effects of an error rate that reduces the per period aggregate agreements of an economy to the actual transactions that eventuate in that period.

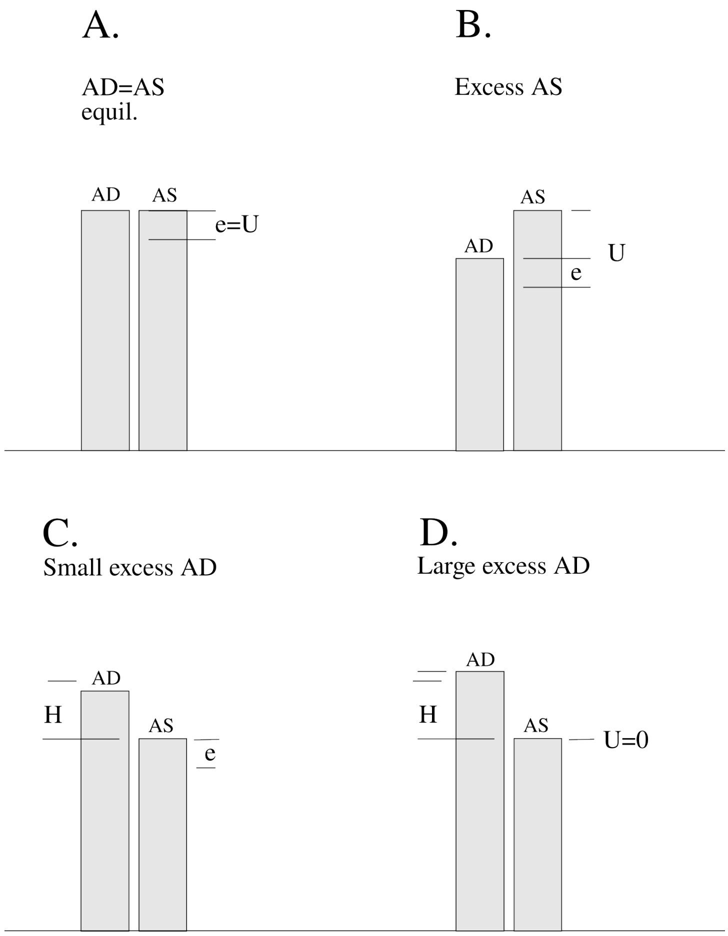

Figure 13: Unemployment as a Function of Aggregate Supply and Demand

<u>Case A. $AD = AS$ equilibrium</u>

In this case the level of agreements, measured in \$ is equal to aggregate supply and aggregate supply. There is no

Case B. Excess AS

Case C. Small excess AD

Case D. Large excess AD

We enumerated four cases above, but we can think about this more abstractly, as each $ being a carrier for a message. We don't need to quantify the amount of information each unit of currency carries. We do need to know what the relative reduction in that quantity is as it is 'transmitted' across the economy. So currency can be thought of as a carrier of economic information that is distributed across the economy, and that its capability of reducing the error rate in this transmission process is dependent on providing redundancy through increases in aggregate amount of currency.

Whatever way we think about the problem, we can use Figure . to determine the increase in F required. The physical bound on market interactions is therefore shown in the Figure below. Case A, C and D are represented on the graph.

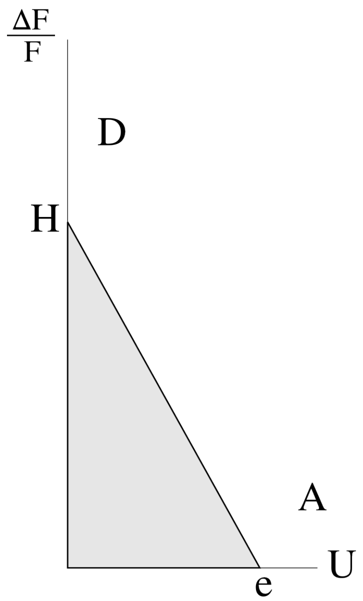

Figure 14: Grey Triangle is the Error Bound

The error bound is a physical contraint on the possibility space of economic interactions. The slope of the line is determined by the mathematical properties of the error rate, and in particular H.

From our simple model of aggregate equilibriation in Section **??** and from equation **??**

$$\frac{\Delta F}{F} = I + G \tag{9}$$

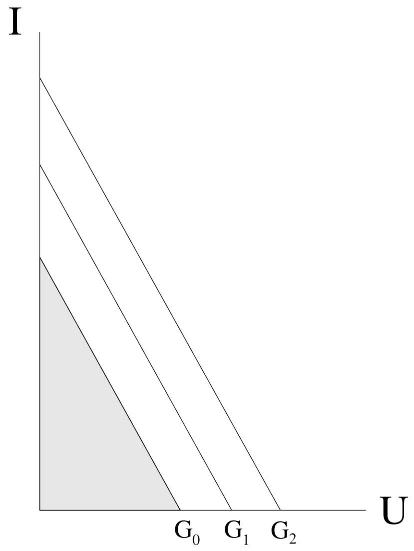

Figure 15: Bound on the Unemployment rate as a function of the Inflation Rate

we can show this bound in terms of the inflation rate I and the unemployment rate U for various different growth rates G, where $G_0 > G_1 > G_2$. Understanding this relation has been central to macroeconomic theory. For instance Fisher Fisher [3] in 1926, Phillips Phillips [11] in 1958 and Lucas [9] all present these relations in graphical form.

We have now been able to shed light on David Hume's problem. His question was why changing units of price should have any affect real quantities. We have now come, at least part-way to solving this problem. However, as we introduce more kinds of transactions into our system, we will find more challenges to the design of a currency that will result in sustained and stable market equilibriation.

4.3 Control

Figure **??** is plotted with the inflation rate on the vertical axis and the unemployment rate on the horizontal axis in accordance to convention. However, the independent variable is the inflation rate, which we control through money supply as indicated in 6. We can control the inflation rate, but in general the growth rate is external to our control. The unemployment bound is a function of I and G. Contraty to convention, the independent variable appears on the vertical axis while the dependent variable appears on the horizontal axis.

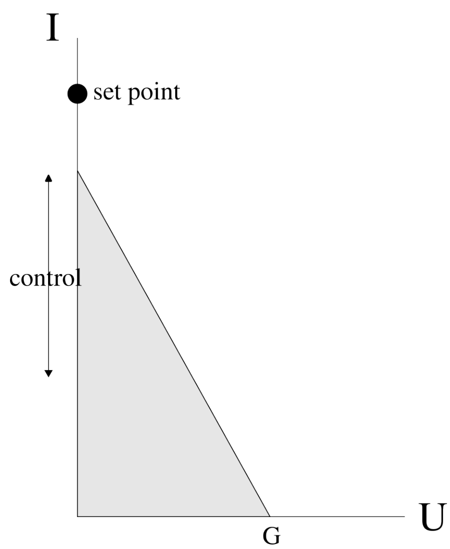

Figure 16: Control for Aggregate Market Equilibriation

Decreasing the unemployment rate to zero requires increasing the inflation rate. At various times in the past, monetary authorities have attempted to reduce the unemployment rate by increasing money supply. At times this has been successful but at times it has resulted in increasing unemployment rates rather than decreasing unemployment rates. In the next section we will examine why this control solution has in many conditions been unsuccessful.

5 Time Transactions

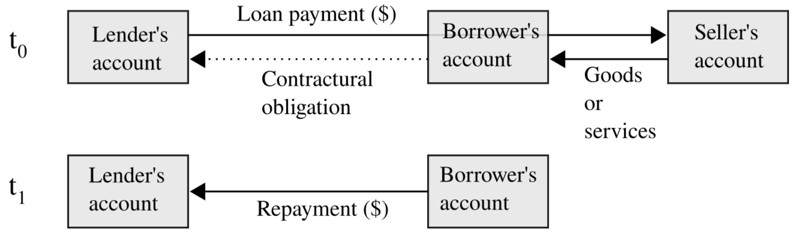

Figure 17: Time Transactions

5.1 Including Time Transactions in Our Model

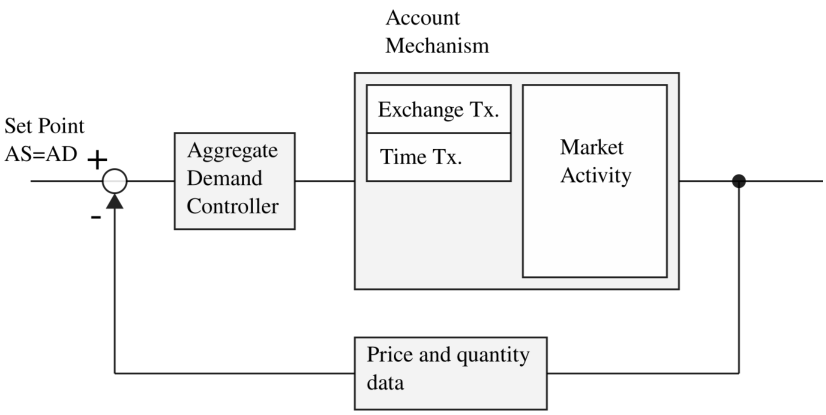

Figure 18: Exchange and Time Transaction Feedback Schema

In Section ?? we showed that there is a bound on the set of economic transactions that are possible, and that the error bound is determined by H (which we can consider as beyond out control), the inflation rate I and the growth rate G. We can control the inflation rate, but in general the growth rate is external to our control. We also showed that to achieve the goals of our currency requires a positive inflation rate. The unit in which we write prices is continuously changing. The unit used to denominate payments in contracts is generally this price unit. We show that this method of choosing interest rates is undercontrollable as discussed in Section ?? such that under conditions of a positive rate of change in the inflation rate, i.e. when

$$\frac{\Delta I}{I} > 0$$

then either the real costs of borrowing must increase or the output Q must decrease. Based on Figure 15 this results in unemployment/inflation tracking that appears as indicated in Figure ??.

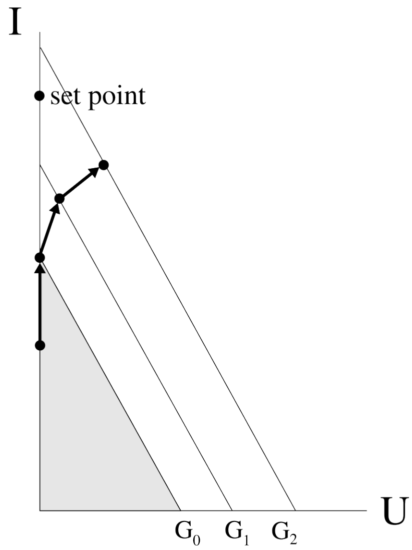

Figure 19: Interest-Inflation Coupling

Control failure occurs until the rate of change in the inflation rate drops to zero or becomes negative. The combination of the error bound and underspecification tracking leads to a fundamental control problem. To set conditions where aggregate equilibrium is possible, the inflation rate must be increased to region D as shown in Figure 15. As the inflation rate increases, uncontrollability tracking reduces the growth rate, increases the unemployment rate. The solution to this problem is to correct the units in which contracts are written. If a unit of account of constant value is used, real interest rates can be trivially specified because the unit directly measures real payments and so fully specifies our control problem. Given that a currency limits transactions to exchange transactions and time transactions, and that a unit of account of constant value is used, and given that there are no other unforseen destabilizing effects, the currency can be controlled to maintain aggregate equilibrium. If a unit of account of constant value is not used, it is not possible for a currency to maintain aggregate equilibrium.

5.2 Interest-Inflation Coupling

We showed in Section **??**. that the unit in which prices are denominated must be continuously changing.

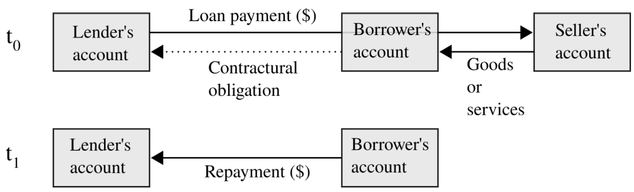

Figure 20: Time Transactions

This unit is used in time transactions to denominate the initial lending of currency, to denominate the repayment, and it is also common practice to use it to specify the repayment in a contract. Because this unit in continuously changing, the value written into contracts must be written in such a way as to specify a real interest rate, i.e. an interest rate written in terms of purchasing power. Fisher [4] notes that in order to specify a real interest rate r then the value i needs to be written into contracts, where

$$i = (1 + r)(1 + I)$$

Whatever real interest rate r lenders and borrows agree upon, its is possible to write the value i into contracts to achieve this outcome. For a given principle k the repayment of the principal is $k(1 + I)$ and the repayment of interest on that principal is $k(1 + I)(1 + r)$, and so total the repayment of both principle and interest is

$$k(1 + r)(1 + I) = k(1 + I) + k(1 + I)(1 + r)$$

From the left-hand side of this equation we can see that the payment denominated in the unit of currency increases at the same rate as the inflation rate. Figure **??**. illustrates that to maintain a market equilibriation set point we need a feedback regulator that responds to deviations in the inflation rate from the set point. Not only does the inflation rate I changes, the rate of change of the inflation rate $\Delta I/I$ changes. This changes the requirement to control the real iterest rate from a single-variable control problem, to a two variable specification problem. For every inflation rate I there are many rates of change of the inflation rate $\Delta I/I$ that affect the real interest rate of a contract. This means that to correctly specify a real interest rate, two number are required, not one. This is a case where our control system is uncontrollable. The real interest rate is a function of i, I and $\Delta I/I$.

$$r = (1+i)\left(1+I\left(1+\frac{\Delta I}{I}\right)\right) = (1+i)\,(1+I+\Delta I) \tag{10}$$

Given that we only have one control, when two are required, we'll look at the effects of controlling the single control we do have.

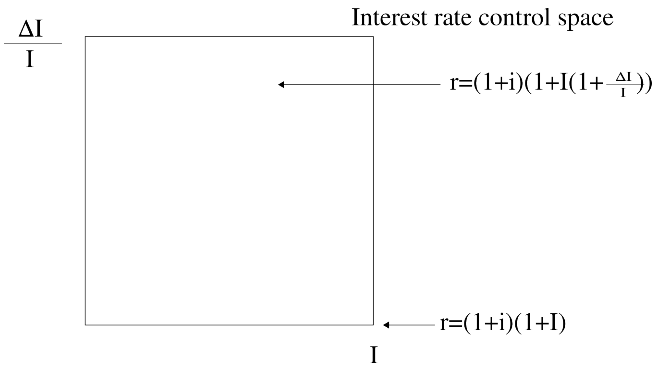

Figure 21: Interest Rate Control Space

We are limited to control options along the horizontal axis. Suppose we are given an r_0 that controls for a given I and where $\Delta I/I = 0$. And then supoose that the rate of change increases so that $\Delta I/I > 0$. The two possible options are to leave i as it is, or to increase i.

<u>Case 1: No change to i</u>

In this case the real interest rate facing lenders will decrease, causing some lender to reject a set of agreements that they would have previously accepted, resulting in decreases in Q and a decrease in the growth rate G.

<u>Case 2: An increase in i</u>

Under these conditions the real costs facing borrowers will increase, causing some lenders to reject a set of agreement that they would have previously accepted, resulting in decreases in Q and a decrease in the growth rate G.

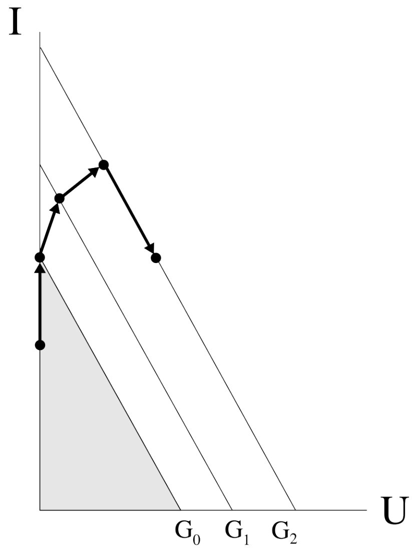

Figure 22: Interest-Inflation Coupling

Because of the shape of the error bound, we can see that if the inflation rate is increased sufficiently, the reduction in the unemployment rate due to increases in the inflation rate can compensate for *all* decreases in the growth rate due to interest control failure. It is possible to double-down on control-failure for a short period of time but maintenance of this state will result in hyper-inflation and high unemployment rates.

The combination of the error bound and interest control failure result in a set point of aggregate equilibrium being unstable, and any attempts to increase the inflation rate toward the set point will leave the system in a state worse, in the sense of a higher unemployment rate, than when it started.

5.3 Solution to Interest-Inflation Coupling

The solution to this problem is to use a unit that directly maps to real interest rates and is independent of the inflation rate, and so also independent of the rate of change of inflation. This unit is termed a unit of account of constant value. To map between this unit of account and prices, the unit of account is multiplied by the price level, and conversely to convert from a price to the unit of account we divide by the price level. The result is a unit that is independent of the exchange rate. Because the value written is independent of the inflation rate, equation (10) becomes

$$r = i$$

As a way of reducing uncertainty in house prices this unit, called the *unidad de formento*, has been used in Chile for several decades [15]. Without interest control failure, the inflation rate can be regulated to a set point in region D of Figure 14.

6 Data

TODO

7 Contract Transactions

7.1 Mechanism

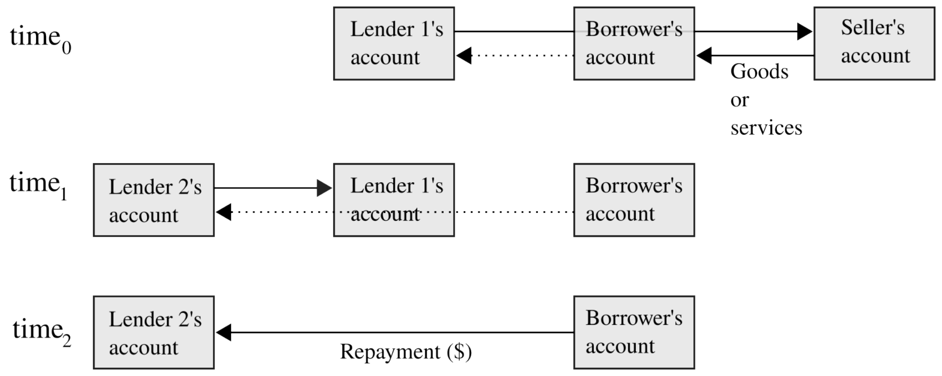

Figure 23: Contract Transactions

7.2 Negative Feedback

There are two money transfers in a contract transaction. The first is a transfer of money in exchange for a good. As with time transactions, interest rates are prices and are subject to excess supply/excess demand response.

7.3 Positive Feedback

A positive feedback can occur if people believe that they can resell something at a later time with a higher price. This may increase demand rather than reduce it as in the negative feedback case. This can occur with both exchange transactions and time transactions if the price of a good is increasing over time. We'll look at the proces in 9. Land and precious metals sometimes behave like this. We'll look at the proces in 9.

7.4 Proxy Accounts

Contract transactions can be used to construct proxy accounts such as bank accounts, that are external to the accounts of the digital currency.

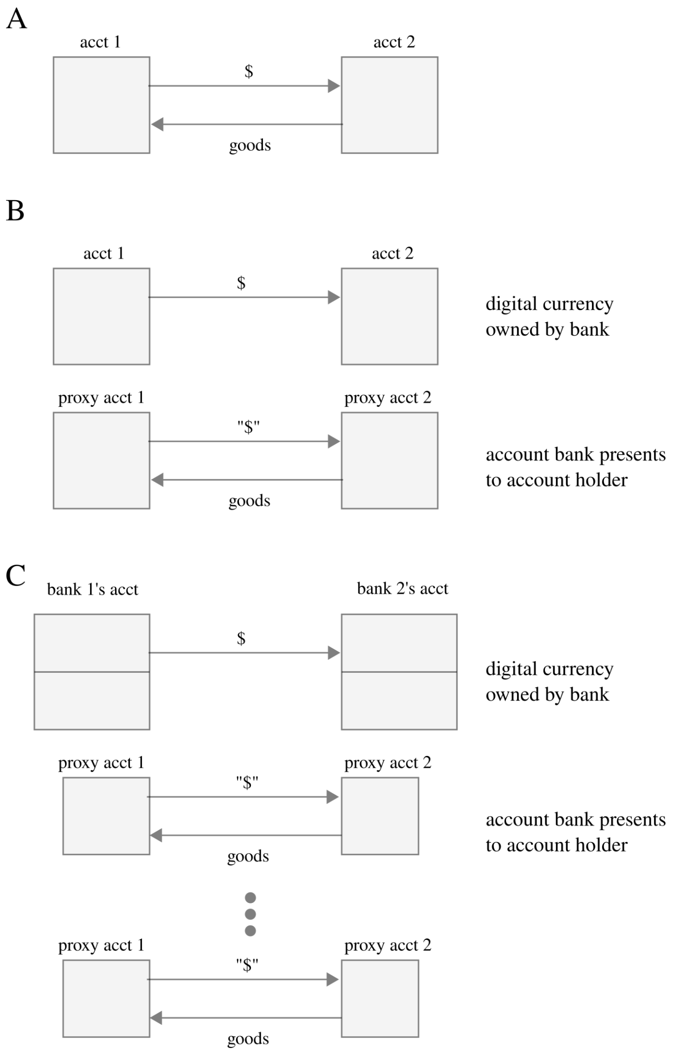

Figure 24: Proxy Accounts

Proxy accounts work by transacting contractural obligations, and adjusting those credits and debts without the need to complete all transactions in the original currency.

Figure **??**, Part A, shows a standard between a standard digitial currency. Part B shows the situation where account holders 1 and 2 have passed responsibility to the management of these accounts to a bank. The banks own accounts in the digital currenct, and present account holders 1 and 2 with a dollar value written on a piece of paper or on a computer, written in the diagram as `"\$"`. When a transaction is made by these two account holders, the bank mirrors this transaction in its digital currency accounts.

Part C shows the situation where bank 1 and bank 2 have many customers, and a single digital currency account that exactly mirrors the aggregate values in all the 'accounts' that the bank presents to the account holders.

It might be possible (and in reality is generally possible) for banks to agree with each other to redeem transactions rather than at the exact time of a transaction but over a certain period of time, such as a day. If the behaviour of the transactions is random meaning that the aggregate flow of transactions from bank 1 to bank 2 cancel out the aggregate flow of transactions from bank 2 to bank 1 over that time period, then banks can use a "fractional reserve system" and reduce that holdings of digital accounts, without any change in the circumstances of the bank account holders. Under a fractional reserve system the flow of transactions through banking accounts can be an order of magnitude greater than through the core digital currency accounts.

This process requires that banks utilize contract transactions between the banks, so that payments are not settled exactly at the time of transaction, are repayed by the end of the period. Time transactions cannot be used as time transactions require a flow of goods between the two parties. So making part C more explicit, we have figure **??**.

7.5 Control of Price Level

As first discussed in Section ??. proxy accounts multiply the supply of money, and introduce problems for the control of the price level.

If there are not proxy accounts it is possible to directly control the total amount of currency through an index mechanism.

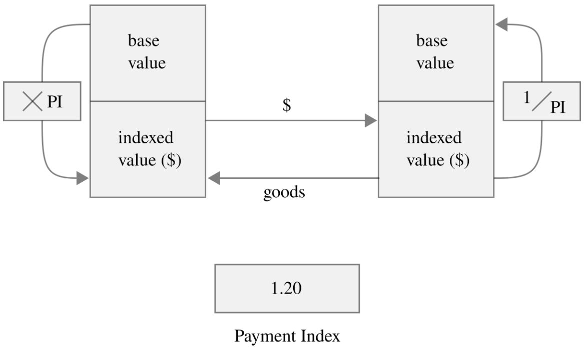

Figure 25: Demand Index Mechanism

The payment index is set by the monetary authority or by algorithm, and is globally accessible. Payment labelling and negotiation and agreements are done in dollars ($). An account holds a base value, which remains constant when there are no transactions. The account holder however sees the dollar value of their account, which is constantly updated as the payment index changes. The dollar value of an account is the produce of the payment index and the base value. The account receiving a payment converts its value into a base value by dividing by the payment index and adding this value to the accounts current base value. Account holders are generally unaware of the base value, and observe a gradually changing dollar value, similar to the way a bank account appends interest payments. All the conversion between base value and dollar value is done automatically by the digital currency.

The monetary authority or algorithm increases or decreases the payment index in order to control aggregate excess supply or aggregate excess demand. In the presence of proxy accounts this control mechanism breaks down. Banking accounts become part of the set of all accounts that through market decisions made by account holders determine aggregate properties of the currency. Traditionally, monetary authorities try to control aggregate values by financial and banking regulations and through what are known are open-market operations, in which monetary authorities try to influence the degree to which banks have contractual obligations with each other by controlling the interest rate at which they can borrow the core digital account currency. This methods has at times been effective at controlling aggregate supply but at other times ineffective. In the absence of proxy accounts, control of the currency through a payment index is direct and likely to be timely, equitable and with high precision. Using this indexation, the tide rises all boats to exactly the same degree. Given that markets remain in equilibriation, the proportional increase in purchasing power is exactly equal to the proportional increase in the price level for every account holder. There is no lag between an increase in the payment index and increase in dollar value in accounts.

7.6 Interaction with Time Transactions

Interest rates in traditional economies are highly correlated as a result of market activity. A rough working model is to think of an economy as having a single interest rate, qualified by “risk”. Both contract transactions and time transactions share this common interest rate. If the interest rate on contract transactions increases due to a positive feedback, at some point it will exceed the market interest rate for time transactions only, resulting in decreases in productive investment through time transactions while investment in a positive feedback bubble is occurring. The dynamics of these kinds of interactions are impossible to predict, both during a positive feedback event and subsequent to the positive feedback event when it is likely that a certain proportion of contracts from time and contract transactions default. In addition, contract transactions are unlimited in complexity of contractual arrangements. It is not possible to create control mechanisms to regulate instabilities that can occur as the result of the use of contract transactions.

7.7 Currency Design and Contract Transactions

To achieve a stable and sustained macro-level equilibrium currencies should be designed to prevent contract transactions for the following reasons:

1. Time transactions can be used for most, possibly all, productive investment.

2. Contract transactions destability price level control.

3. Contract transactions can destabilize the interest rate which affects time transactions.

4. Positive feedback in contract transactions are the most common cause of financial bubbles and crashes.

8 External Transactions

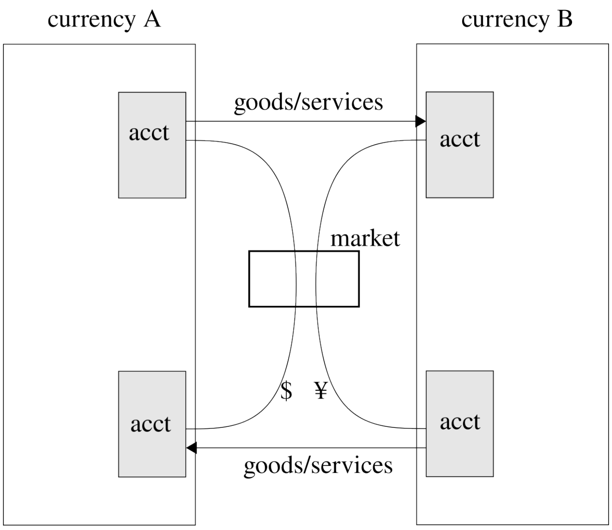

Figure 26: External Transactions

Figure 26 shows an external transaction. Without some extra form of coordination, implemented by some additional accounts, the transaction as it stands in the figure would be very difficult to coodinate. But it captures the important property of external transactions, that across the market boundaries the exchange rate is the rate of payments in currency A as a ratio of the rate of payments in currency B.

$$X = \frac{A}{B}$$

where X is the exchange rate and the unit is

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

Following our program, we'll look at how external transactions interact with other transaction types.

8.1 External Transactions and Exchange Transactions

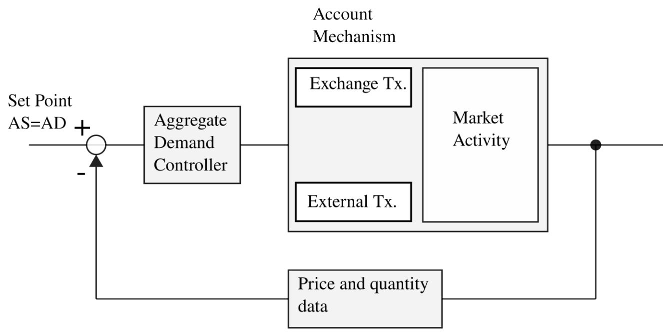

Figure 27: Interaction of External and Exchange Transactions

There is a negative feedback stabilizing process that brings the exchange rate into equilibrium with the relative price levels of the two currencies. This process was described by Cassel [2] in 1914. If

$$\frac{P_A}{P_B} > \frac{A}{B}$$

the goods and services in currency B are cheaper than goods and services in currency A, and so exports of goods and services from B to A increase, and exports of goods and services from A to B decrease. This process continues until an equilibrium where

$$\frac{P_A}{P_B} \doteq \frac{A}{B}$$

where $\doteq$ represents the equilibrium state.

8.2 External Transactions and Time Transactions

Because time transactions also involve the exchange of goods and services, time transactions also contribute to the stabilization process described in the previous section. Repayments across the external transaction market are determined in earlier periods from short term to long term contracts, and therefore do not have the equilibriating "power" that exchange transactions do. Interest rate differentials across the two currencies are liable to cause unpredictable disturbances across the two currencies.

8.3 External Transactions and Contract Transactions

Contract transactions are only minimally connected to an initial exchange transactions, but can involve multiple and continuing payments for changes in contract status. This proces is liable to cause strong disturbances unrelated to the equilibriating process, and therefore are highly likely to introduce disturbances to the exchange rate equilibriating process. Exchange rates across legacy currencies that have floating exchange rates can and often do experience rapid fluctuations in exchange rates.

8.4 Control of External Exchange

If only exchange transactions are allowed as external transactions the exchange rate should equilibriate to the relative prices levels of the two currencies, otherwise know as purchasing power parity. The introduction of contract transactions are highly likely to cause disturbances to both currencies, making it difficult to maintain macro-equilibriation goals. Time transactions, represent a middle-ground between contract and exchange transactions.

9 Other Transactions

If the price a good or service can be resold at a higher price then another form of transaction is possible. This transaction can induce a positive feedback loop as an increase in prices over time cause other economic participants to enter the market, further increasing prices. Often part or all of the motivation for buying land or precious metals is to transact in this way. One method to prevent or limit this positive feedback instability is to use a separate currency for certain classes of goods category, for example to use a specific currency to real-estate transactions. By doing this it is possible to fix the exchange rate between the two currencies as an index that tracks the average increases in prices of real-estate. Then a conversion between the two currencies compensates for average changes in the price of this good.

10 Implementation

10.1 Demand Indexation

The demand index is a value published by a monetary authority or an algorithm. It directly adjusts the total money supply by indexing all account values. Accounts exist as a base value. The values appearing in called face values. The face value is a multiple of the base value and the demand index. Prices are denominated in this value, and base values are generally hidden from the user. Base values are transfered between accounts.

10.2 Exchange Transactions

Valid exchange transactions require a record of the payment, the quantity of goods to be transactions, and the goods category. It is always possible for buyers and sellers to collude to write in incorrect goods categories. The importance of recording the goods category is for measuring aggregate properties of a currency's transactions, and also to record that the transaction was indeed an exchange transaction and that no future contractural obligations remain. By using exchange transactions buyers and seller forfeit all future financial obligations, thereby reducing the utility of using exchange transactions for facilitating contract transactions.

10.3 Data Record

A record of transaction payment, goods category and quantity of goods are recorded, and used to calculate the Q, P and F. The price index P is published and used for calculation of time transactions. Methods to protect the privacy of accounts must be used.

10.4 Indexed Unit of Account

10.5 Time Transactions

Time transactions involve an initial payment and a later repayment. All monetary values in contracts for time transactions are written in indexed units of account and repayments are not facilitated on contracts in other units. The indexed unit of account records a base value which is then indexed by the price index. The receiving account for repayments for time transactions must be the same account from which the initial payment is made.

10.6 Contract Transactions

Contract transactions are prevented by only allowing repayments of time transactions into the same account from which the initial payment is made. Transactions that are not recorded as time transactions are not acceptable for setting up financial contractural obligations, so no party has any financial legal rights beyond time transactions. There remains likelihood that other transactions are used to achieve contract transactions, but the important requirement is that contract transactions are sufficiently limited to prevent effects that disturb the economy at aggregate level through interest rates, disturbance of control of aggregate demand, or positive feedback in speculative activity.

10.7 Control

The demand index is determined using the data record so as to regulate $\Delta F/F$. Occassional unemployment surveys may be taken to confirm that the set point for $\Delta F/F$ is sufficiently high.

10.8 Intermediate Accounts

Because exchange transactions require a record of goods category, there is a need for intermediate accounts that sit between accounts that make exchange transactions. They also can be used as shared accounts. For example, membership fees are not directly associated with exchange transactions. Intermediate accounts must not interact directly with other intermediate accounts.

10.9 External Transactions

External transactions are not initially essential to a currency and introduce risk as they require interaction with other currencies. Once several currencesy are sufficiently established and reliable it may be possible to introduce extenal transactions. The external transaction mechanism would need a way to resolve coordination problems. One reasonable possibility would be to have special external transaction accounts which are limited in size, and have a fixed exchange rate that is the ratio of the price indices of the two currencies.

11 Conclusion

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

<u>The error effect and Fisher lines</u>

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

<u>Aggregate equilibrium</u>

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.

<u>Inflation feedback and financial bubbles and crashes</u>

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.

<u>Market driven changes in aggregate quantities and prices</u>

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.

References

[1] Stuart Bennet, *A Brief History of Automatic Control*, IEEE Control Systems Magazine, volume 16, issue 3, June 1996, pages 17-25, doi: 10.1109/37.506394.

[2] Gustav Cassel, *Money and Foreign Exchange After 1914*, Macmillan, 1923, p.137.

[3] Irving Fisher, *A Statistical Relation between Unemployment and Price Changes* International Labour Review, 1926, volume 13, pages 496-502, 1926.

[4] Irving Fisher, *The Rate of Interest*, Macmillan Company, 1907.

[5] R.W.Hamming, *Error Detecting and Error Correcting Codes*, The Bell System Technical Journal, volume 14, number 2, April 1950, pages 147-160.

[6] T.P.Hughes, *Elmer Sperry: Inventor and Engineer* 1971.

[7] David Hume, *Of Money, Essays, Moral, Political and Literary*, 1741.

[8] Leslie Lamport, *Proving the Correctness of Multiprocess Programs* IEEE Transactions of Software Engineering, volume SE-3, number 2, March 1977.

[9] Robert E. Lucas Jr., *Nobel Lecture: Money Neutrality*, The Journal of Political Economy, 1996, volume 104, pages 661-682.

[10] David J.S. MacKay, *Information Theory, Inference, and Learning Algorithms*, Cambridge University Press, 2003.

[11] A.W. Phillips, *The Relation between Unemployment and the Rate of Change of Money Wage Rates in the United Kingdom, 1861-1957*, Economica, 1958, volume 25, pages 283-299.

[12] RFC 896, *Congestion Control in IP/TCP Internetworks*, John Nagle, January 1984.

[13] Lawrence Roberts, *The Evolution of Packet Switching*, Proceedings of the IEEE, December 1978.

[14] Claude E. Shannon, *A Mathematical Theory of Communication*, The Bell System Technical Journal, volume 27, pages 379-412, 1948.

[15] Robert J Shiller, *Indexed Units of Account: Theory and Assessment of Historical Experience*, NBER Working Paper Series, volume 6356, 1998.

[16] J. Clerk Maxwell, *On Governors*, March 5, 1968.

[17] Nicolas Minorsky, *Directional Stability of Automatically Steered Bodies*, Naval Engineers Journal, volume 32, issue number 2, 1922.

[18] Elmer A. Sperry, *Engineering Applications of the Gyroscope*, Journal of the Franklin Institute, volume 175, Number 5, May 1913.

[19] Orville and Wilbur Wright, *The Wright Brothers Aeroplane*, Century Magazine, September 1908.