*Andreas M. Antonopoulos*

Bitcoin is a collection of concepts and technologies that form the basis of a digital money

ecosystem. Units of currency called bitcoins are used to store and transmit value among

participants in the bitcoin network. Bitcoin users communicate with each other using

the bitcoin protocol primarily via the Internet, although other transport networks can

also be used. The bitcoin protocol stack, available as open source software, can be run

on a wide range of computing devices, including laptops and smartphones, making the

technology easily accessible.

Users can transfer bitcoins over the network to do just about anything that can be done

with conventional currencies, including buy and sell goods, send money to people or

organizations, or extend credit. Bitcoins can be purchased, sold, and exchanged for

other currencies at specialized currency exchanges. Bitcoin in a sense is the perfect form

of money for the Internet because it is fast, secure, and borderless.

Unlike traditional currencies, bitcoins are entirely virtual. There are no physical coins

or even digital coins per se. The coins are implied in transactions that transfer value

from sender to recipient. Users of bitcoin own keys that allow them to prove ownership

of transactions in the bitcoin network, unlocking the value to spend it and transfer it to

a new recipient. Those keys are often stored in a digital wallet on each user’s computer.

Possession of the key that unlocks a transaction is the only prerequisite to spending

bitcoins, putting the control entirely in the hands of each user.

Bitcoin is a distributed, peer-to-peer system. As such there is no “central” server or point

of control. Bitcoins are created through a process called “mining,” which involves competing

to find solutions to a mathematical problem while processing bitcoin transactions.

Any participant in the bitcoin network (i.e., anyone using a device running the

full bitcoin protocol stack) may operate as a miner, using their computer’s processing

power to verify and record transactions. Every 10 minutes on average, someone is able

1

to validate the transactions of the past 10 minutes and is rewarded with brand new

bitcoins. Essentially, bitcoin mining decentralizes the currency-issuance and clearing

functions of a central bank and replaces the need for any central bank with this global

competition.

The bitcoin protocol includes built-in algorithms that regulate the mining function

across the network. The difficulty of the processing task that miners must perform—to

successfully record a block of transactions for the bitcoin network—is adjusted dynamically

so that, on average, someone succeeds every 10 minutes regardless of how

many miners (and CPUs) are working on the task at any moment. The protocol also

halves the rate at which new bitcoins are created every four years, and limits the total

number of bitcoins that will be created to a fixed total of 21 million coins. The result is

that the number of bitcoins in circulation closely follows an easily predictable curve that

reaches 21 million by the year 2140. Due to bitcoin’s diminishing rate of issuance, over

the long term, the bitcoin currency is deflationary. Furthermore, bitcoin cannot be inflated

by “printing” new money above and beyond the expected issuance rate.

Behind the scenes, bitcoin is also the name of the protocol, a network, and a distributed

computing innovation. The bitcoin currency is really only the first application of this

invention. As a developer, I see bitcoin as akin to the Internet of money, a network for

propagating value and securing the ownership of digital assets via distributed computation.

There’s a lot more to bitcoin than first meets the eye.

In this chapter we’ll get started by explaining some of the main concepts and terms,

getting the necessary software, and using bitcoin for simple transactions. In following

chapters we’ll start unwrapping the layers of technology that make bitcoin possible and

examine the inner workings of the bitcoin network and protocol.

Digital Currencies Before Bitcoin

The emergence of viable digital money is closely linked to developments in cryptography.

This is not surprising when one considers the fundamental challenges involved

with using bits to represent value that can be exchanged for goods and services. Two

basic questions for anyone accepting digital money are:

1. Can I trust the money is authentic and not counterfeit?

2. Can I be sure that no one else can claim that this money belongs to them and not

me? (Aka the “double-spend” problem.)

Issuers of paper money are constantly battling the counterfeiting problem by using

increasingly sophisticated papers and printing technology. Physical money addresses

the double-spend issue easily because the same paper note cannot be in two places at

once. Of course, conventional money is also often stored and transmitted digitally. In

these cases, the counterfeiting and double-spend issues are handled by clearing all elec‐

2 | Chapter 1: Introduction

tronic transactions through central authorities that have a global view of the currency

in circulation. For digital money, which cannot take advantage of esoteric inks or holographic

strips, cryptography provides the basis for trusting the legitimacy of a user’s

claim to value. Specifically, cryptographic digital signatures enable a user to sign a digital

asset or transaction proving the ownership of that asset. With the appropriate architecture,

digital signatures also can be used to address the double-spend issue.

When cryptography started becoming more broadly available and understood in the

late 1980s, many researchers began trying to use cryptography to build digital currencies.

These early digital currency projects issued digital money, usually backed by a

national currency or precious metal such as gold.

Although these earlier digital currencies worked, they were centralized and, as a result,

they were easy to attack by governments and hackers. Early digital currencies used a

central clearinghouse to settle all transactions at regular intervals, just like a traditional

banking system. Unfortunately, in most cases these nascent digital currencies were targeted

by worried governments and eventually litigated out of existence. Some failed in

spectacular crashes when the parent company liquidated abruptly. To be robust against

intervention by antagonists, whether legitimate governments or criminal elements, a

decentralized digital currency was needed to avoid a single point of attack. Bitcoin is

such a system, completely decentralized by design, and free of any central authority or

point of control that can be attacked or corrupted.

Bitcoin represents the culmination of decades of research in cryptography and distributed

systems and includes four key innovations brought together in a unique and

powerful combination. Bitcoin consists of:

• A decentralized peer-to-peer network (the bitcoin protocol)

• A public transaction ledger (the blockchain)

• A decentralized mathematical and deterministic currency issuance (distributed

mining)

• A decentralized transaction verification system (transaction script)

History of Bitcoin

Bitcoin was invented in 2008 with the publication of a paper titled “Bitcoin: A Peer-to-

Peer Electronic Cash System,” written under the alias of Satoshi Nakamoto. Nakamoto

combined several prior inventions such as b-money and HashCash to create a completely

decentralized electronic cash system that does not rely on a central authority for

currency issuance or settlement and validation of transactions. The key innovation was

to use a distributed computation system (called a “proof-of-work” algorithm) to conduct

a global “election” every 10 minutes, allowing the decentralized network to arrive at

*consensus* about the state of transactions. This elegantly solves the issue of double-spend

History of Bitcoin | 3

where a single currency unit can be spent twice. Previously, the double-spend problem

was a weakness of digital currency and was addressed by clearing all transactions

through a central clearinghouse.

The bitcoin network started in 2009, based on a reference implementation published

by Nakamoto and since revised by many other programmers. The distributed computation

that provides security and resilience for bitcoin has increased exponentially, and

now exceeds that combined processing capacity of the world’s top super-computers.

Bitcoin’s total market value is estimated at between 5 billion and 10 billion US dollars,

depending on the bitcoin-to-dollar exchange rate. The largest transaction processed so

far by the network was 150 million US dollars, transmitted instantly and processed

without any fees.

Satoshi Nakamoto withdrew from the public in April of 2011, leaving the responsibility

of developing the code and network to a thriving group of volunteers. The identity of

the person or people behind bitcoin is still unknown. However, neither Satoshi Nakamoto

nor anyone else exerts control over the bitcoin system, which operates based on

fully transparent mathematical principles. The invention itself is groundbreaking and

has already spawned new science in the fields of distributed computing, economics, and

econometrics.

A Solution to a Distributed Computing Problem

Satoshi Nakamoto’s invention is also a practical solution to a previously unsolved problem

in distributed computing, known as the “Byzantine Generals’ Problem.” Briefly, the

problem consists of trying to agree on a course of action by exchanging information

over an unreliable and potentially compromised network. Satoshi Nakamoto’s solution,

which uses the concept of proof-of-work to achieve consensus without a central trusted

authority, represents a breakthrough in distributed computing science and has wide

applicability beyond currency. It can be used to achieve consensus on decentralized

networks to prove the fairness of elections, lotteries, asset registries, digital notarization,

and more.

Bitcoin Uses, Users, and Their Stories

Bitcoin is a technology, but it expresses money that is fundamentally a language for

exchanging value between people. Let’s look at the people who are using bitcoin and

some of the most common uses of the currency and protocol through their stories. We

will reuse these stories throughout the book to illustrate the real-life uses of digital

money and how they are made possible by the various technologies that are part of

bitcoin.

4 | Chapter 1: Introduction

*North American low-value retail*

Alice lives in Northern California’s Bay Area. She has heard about bitcoin from her

techie friends and wants to start using it. We will follow her story as she learns about

bitcoin, acquires some, and then spends some of her bitcoin to buy a cup of coffee

at Bob’s Cafe in Palo Alto. This story will introduce us to the software, the exchanges,

and basic transactions from the perspective of a retail consumer.

*North American high-value retail*

Carol is an art gallery owner in San Francisco. She sells expensive paintings for

bitcoin. This story will introduce the risks of a “51%” consensus attack for retailers

of high-value items.

*Offshore contract services*

Bob, the cafe owner in Palo Alto, is building a new website. He has contracted with

an Indian web developer, Gopesh, who lives in Bangalore, India. Gopesh has agreed

to be paid in bitcoin. This story will examine the use of bitcoin for outsourcing,

contract services, and international wire transfers.

*Charitable donations*

Eugenia is the director of a children’s charity in the Philippines. Recently she has

discovered bitcoin and wants to use it to reach a whole new group of foreign and

domestic donors to fundraise for her charity. She’s also investigating ways to use

bitcoin to distribute funds quickly to areas of need. This story will show the use of

bitcoin for global fundraising across currencies and borders and the use of an open

ledger for transparency in charitable organizations.

*Import/export*

Mohammed is an electronics importer in Dubai. He’s trying to use bitcoin to buy

electronics from the US and China for import into the UAE to accelerate the process

of payments for imports. This story will show how bitcoin can be used for large

business-to-business international payments tied to physical goods.

*Mining for bitcoin*

Jing is a computer engineering student in Shanghai. He has built a “mining” rig to

mine for bitcoins, using his engineering skills to supplement his income. This story

will examine the “industrial” base of bitcoin: the specialized equipment used to

secure the bitcoin network and issue new currency.

Each of these stories is based on real people and real industries that are currently using

bitcoin to create new markets, new industries, and innovative solutions to global economic

issues.

Bitcoin Uses, Users, and Their Stories | 5

Getting Started

To join the bitcoin network and start using the currency, all a user has to do is download

an application or use a web application. Because bitcoin is a standard, there are many

implementations of the bitcoin client software. There is also a reference implementation,

also known as the Satoshi client, which is managed as an open source project by a team

of developers and is derived from the original implementation written by Satoshi Nakamoto.

The three main forms of bitcoin clients are:

*Full client*

A full client, or “full node,” is a client that stores the entire history of bitcoin transactions

(every transaction by every user, ever), manages the users’ wallets, and can

initiate transactions directly on the bitcoin network. This is similar to a standalone

email server, in that it handles all aspects of the protocol without relying on any

other servers or third-party services.

*Lightweight client*

A lightweight client stores the user’s wallet but relies on third-party–owned servers

for access to the bitcoin transactions and network. The light client does not store a

full copy of all transactions and therefore must trust the third-party servers for

transaction validation. This is similar to a standalone email client that connects to

a mail server for access to a mailbox, in that it relies on a third party for interactions

with the network.

*Web client*

Web clients are accessed through a web browser and store the user’s wallet on a

server owned by a third party. This is similar to webmail in that it relies entirely on

a third-party server.

Mobile Bitcoin

Mobile clients for smartphones, such as those based on the Android system, can either

operate as full clients, lightweight clients, or web clients. Some mobile clients are

synchronized with a web or desktop client, providing a multiplatform wallet across

multiple devices but with a common source of funds.

The choice of bitcoin client depends on how much control the user wants over funds.

A full client will offer the highest level of control and independence for the user, but in

turn puts the burden of backups and security on the user. On the other end of the range

of choices, a web client is the easiest to set up and use, but the trade-off with a web client

is that counterparty risk is introduced because security and control is shared with the

user and the owner of the web service. If a web-wallet service is compromised, as many

6 | Chapter 1: Introduction

have been, the users can lose all their funds. Conversely, if users have a full client without

adequate backups, they might lose their funds through a computer mishap.

For the purposes of this book, we will be demonstrating the use of a variety of downloadable

bitcoin clients, from the reference implementation (the Satoshi client) to web

wallets. Some of the examples will require the use of the reference client, which, in

addition to being a full client, also exposes APIs to the wallet, network, and transaction

services. If you are planning to explore the programmatic interfaces into the bitcoin

system, you will need the reference client.

Quick Start

Alice, who we introduced in “Bitcoin Uses, Users, and Their Stories” on page 4, is not

a technical user and only recently heard about bitcoin from a friend. She starts her

journey by visiting the official website bitcoin.org, where she finds a broad selection of

bitcoin clients. Following the advice on the bitcoin.org site, she chooses the lightweight

bitcoin client Multibit.

Alice follows a link from the bitcoin.org site to download and install Multibit on her

desktop. Multibit is available for Windows, Mac OS, and Linux desktops.

A bitcoin wallet must be protected by a password or passphrase.

There are many bad actors attempting to break weak passwords, so

take care to select one that cannot be easily broken. Use a combination

of upper and lowercase characters, numbers, and symbols.

Avoid personal information such as birth dates or names of sports

teams. Avoid any words commonly found in dictionaries, in any

language. If you can, use a password generator to create a completely

random password that is at least 12 characters in length. Remember:

bitcoin is money and can be instantly moved anywhere in the

world. If it is not well protected, it can be easily stolen.

Once Alice has downloaded and installed the Multibit application, she runs it and is

greeted by a Welcome screen, as shown in Figure 1-1.

Getting Started | 7

*Figure 1-1. The Multibit bitcoin client Welcome screen*

Multibit automatically creates a wallet and a new bitcoin address for Alice, which Alice

can see by clicking the Request tab shown in Figure 1-2.

*Figure 1-2. Alice’s new bitcoin address, in the Request tab of the Multibit client*

The most important part of this screen is Alice’s *bitcoin address*. Like an email address,

Alice can share this address and anyone can use it to send money directly to her new

wallet. On the screen it appears as a long string of letters and numbers:

1Cdid9KFAaatwczBwBttQcwXYCpvK8h7FK. Next to the wallet’s bitcoin address is a QR

8 | Chapter 1: Introduction

code, a form of barcode that contains the same information in a format that can be

scanned by a smartphone camera. The QR code is the black-and-white square on the

right side of the window. Alice can copy the bitcoin address or the QR code onto her

clipboard by clicking the copy button adjacent to each of them. Clicking the QR code

itself will magnify it, so that it can be easily scanned by a smartphone camera.

Alice can also print the QR code as a way to easily give her address to others without

them having to type the long string of letters and numbers.

Bitcoin addresses start with the digit 1 or 3. Like email addresses, they

can be shared with other bitcoin users who can use them to send

bitcoin directly to your wallet. Unlike email addresses, you can create

new addresses as often as you like, all of which will direct funds

to your wallet. A wallet is simply a collection of addresses and the keys

that unlock the funds within. You can increase your privacy by using

a different address for every transaction. There is practically no

limit to the number of addresses a user can create.

Alice is now ready to start using her new bitcoin wallet.

Getting Your First Bitcoins

It is not possible to buy bitcoins at a bank or foreign exchange kiosks at this time. As of

2014, it is still quite difficult to acquire bitcoins in most countries. There are a number

of specialized currency exchanges where you can buy and sell bitcoin in exchange for

a local currency. These operate as web-based currency markets and include:

*Bitstamp*

A European currency market that supports several currencies including euros

(EUR) and US dollars (USD) via wire transfer.

*Coinbase*

A US-based bitcoin wallet and platform where merchants and consumers can

transact in bitcoin. Coinbase makes it easy to buy and sell bitcoin, allowing users

to connect to US checking accounts via the ACH system.

Cryptocurrency exchanges such as these operate at the intersection of national currencies

and cryptocurrencies. As such, they are subject to national and international regulations,

and are often specific to a single country or economic area and specialize in

the national currencies of that area. Your choice of currency exchange will be specific

to the national currency you use and limited to the exchanges that operate within the

legal jurisdiction of your country. Similar to opening a bank account, it takes several

days or weeks to set up the necessary accounts with these services because they require

various forms of identification to comply with KYC (know your customer) and AML

(anti-money laundering) banking regulations. Once you have an account on a bitcoin

Getting Started | 9

exchange, you can then buy or sell bitcoins quickly just as you could with foreign currency

with a brokerage account.

You can find a more complete list at bitcoin charts, a site that offers price quotes and

other market data across many dozens of currency exchanges.

There are four other methods for getting bitcoins as a new user:

• Find a friend who has bitcoins and buy some from him directly. Many bitcoin users

start this way.

• Use a classified service such as localbitcoins.com to find a seller in your area to buy

bitcoins for cash in an in-person transaction.

• Sell a product or service for bitcoin. If you’re a programmer, sell your programming

skills.

• Use a bitcoin ATM in your city. Find a bitcoin ATM close to you using an online

map from CoinDesk.

Alice was introduced to bitcoin by a friend and so she has an easy way of getting her

first bitcoins while she waits for her account on a California currency market to be

verified and activated.

Sending and Receiving Bitcoins

Alice has created her bitcoin wallet and she is now ready to receive funds. Her wallet

application randomly generated a private key (described in more detail in “Private

Keys” on page 63) together with its corresponding bitcoin address. At this point, her

bitcoin address is not known to the bitcoin network or “registered” with any part of the

bitcoin system. Her bitcoin address is simply a number that corresponds to a key that

she can use to control access to the funds. There is no account or association between

that address and an account. Until the moment this address is referenced as the recipient

of value in a transaction posted on the bitcoin ledger (the blockchain), it is simply part

of the vast number of possible addresses that are “valid” in bitcoin. Once it has been

associated with a transaction, it becomes part of the known addresses in the network

and Alice can check its balance on the public ledger.

Alice meets her friend Joe, who introduced her to bitcoin, at a local restaurant so they

can exchange some US dollars and put some bitcoins into her account. She has brought

a printout of her address and the QR code as displayed in her bitcoin wallet. There is

nothing sensitive, from a security perspective, about the bitcoin address. It can be posted

anywhere without risking the security of her account.

Alice wants to convert just 10 US dollars into bitcoin, so as not to risk too much money

on this new technology. She gives Joe a $10 bill and the printout of her address so that

Joe can send her the equivalent amount of bitcoin.

10 | Chapter 1: Introduction

Next, Joe has to figure out the exchange rate so that he can give the correct amount of

bitcoin to Alice. There are hundreds of applications and websites that can provide the

current market rate. Here are some of the most popular:

*Bitcoin Charts*

A market data listing service that shows the market rate of bitcoin across many

exchanges around the globe, denominated in different local currencies

*Bitcoin Average*

A site that provides a simple view of the volume-weighted-average for each currency

*ZeroBlock*

A free Android and iOS application that can display a bitcoin price from different

exchanges (see Figure 1-3)

*Bitcoin Wisdom*

Another market data listing service

*Figure 1-3. ZeroBlock, a bitcoin market-rate application for Android and iOS*

Using one of the applications or websites just listed, Joe determines the price of bitcoin

to be approximately 100 US dollars per bitcoin. At that rate he should give Alice 0.10

bitcoin, also known as 100 millibits, in return for the 10 US dollars she gave him.

Once Joe has established a fair exchange price, he opens his mobile wallet application

and selects to “send” bitcoin. For example, if using the Blockchain mobile wallet on an

Android phone, he would see a screen requesting two inputs, as shown in Figure 1-4.

• The destination bitcoin address for the transaction

• The amount of bitcoin to send

In the input field for the bitcoin address, there is a small icon that looks like a QR code.

This allows Joe to scan the barcode with his smartphone camera so that he doesn’t have

to type in Alice’s bitcoin address (1Cdid9KFAaatwczBwBttQcwXYCpvK8h7FK), which is

quite long and difficult to type. Joe taps the QR code icon and activates the smartphone

camera, scanning the QR code from Alice’s printed wallet that she brought with her.

The mobile wallet application fills in the bitcoin address and Joe can check that it scan‐

Getting Started | 11

ned correctly by comparing a few digits from the address with the address printed by

Alice.

*Figure 1-4. Blockchain mobile wallet’s bitcoin send screen*

Joe then enters the bitcoin value for the transaction, 0.10 bitcoin. He carefully checks

to make sure he has entered the correct amount, because he is about to transmit money

and any mistake could be costly. Finally, he presses Send to transmit the transaction.

Joe’s mobile bitcoin wallet constructs a transaction that assigns 0.10 bitcoin to the address

provided by Alice, sourcing the funds from Joe’s wallet and signing the transaction

with Joe’s private keys. This tells the bitcoin network that Joe has authorized a transfer

of value from one of his addresses to Alice’s new address. As the transaction is transmitted

via the peer-to-peer protocol, it quickly propagates across the bitcoin network.

In less than a second, most of the well-connected nodes in the network receive the

transaction and see Alice’s address for the first time.

If Alice has a smartphone or laptop with her, she will also be able to see the transaction.

The bitcoin ledger—a constantly growing file that records every bitcoin transaction that

has ever occurred—is public, meaning that all she has to do is look up her own address

and see if any funds have been sent to it. She can do this quite easily at the blockchain.info

website by entering her address in the search box. The website will show her a page

listing all the transactions to and from that address. If Alice is watching that page, it will

update to show a new transaction transferring 0.10 bitcoin to her balance soon after Joe

hits Send.

12 | Chapter 1: Introduction

Confirmations

At first, Alice’s address will show the transaction from Joe as “Unconfirmed.” This means

that the transaction has been propagated to the network but has not yet been included

in the bitcoin transaction ledger, known as the blockchain. To be included, the transaction

must be “picked up” by a miner and included in a block of transactions. Once a

new block is created, in approximately 10 minutes, the transactions within the block

will be accepted as “confirmed” by the network and can be spent. The transaction is seen

by all instantly, but it is only “trusted” by all when it is included in a newly mined block.

Alice is now the proud owner of 0.10 bitcoin that she can spend. In the next chapter we

will look at her first purchase with bitcoin, and examine the underlying transaction and

propagation technologies in more detail.

Getting Started | 13

CHAPTER 2

How Bitcoin Works

Transactions, Blocks, Mining, and the Blockchain

The bitcoin system, unlike traditional banking and payment systems, is based on decentralized

trust. Instead of a central trusted authority, in bitcoin, trust is achieved as

an emergent property from the interactions of different participants in the bitcoin system.

In this chapter, we will examine bitcoin from a high level by tracking a single

transaction through the bitcoin system and watch as it becomes “trusted” and accepted

by the bitcoin mechanism of distributed consensus and is finally recorded on the blockchain,

the distributed ledger of all transactions.

Each example is based on an actual transaction made on the bitcoin network, simulating

the interactions between the users (Joe, Alice, and Bob) by sending funds from one

wallet to another. While tracking a transaction through the bitcoin network and blockchain,

we will use a *blockchain explorer* site to visualize each step. A blockchain explorer

is a web application that operates as a bitcoin search engine, in that it allows you to

search for addresses, transactions, and blocks and see the relationships and flows between

them.

Popular blockchain explorers include:

• Blockchain info

• Bitcoin Block Explorer

• insight

• blockr Block Reader

Each of these has a search function that can take an address, transaction hash, or block

number and find the equivalent data on the bitcoin network and blockchain. With each

example, we will provide a URL that takes you directly to the relevant entry, so you can

study it in detail.

15

Bitcoin Overview

In the overview diagram shown in Figure 2-1, we see that the bitcoin system consists

of users with wallets containing keys, transactions that are propagated across the network,

and miners who produce (through competitive computation) the consensus

blockchain, which is the authoritative ledger of all transactions. In this chapter, we will

trace a single transaction as it travels across the network and examine the interactions

between each part of the bitcoin system, at a high level. Subsequent chapters will delve

into the technology behind wallets, mining, and merchant systems.

*Figure 2-1. Bitcoin overview*

Buying a Cup of Coffee

Alice, introduced in the previous chapter, is a new user who has just acquired her first

bitcoin. In “Getting Your First Bitcoins” on page 9, Alice met with her friend Joe to

exchange some cash for bitcoin. The transaction created by Joe funded Alice’s wallet

with 0.10 BTC. Now Alice will make her first retail transaction, buying a cup of coffee

at Bob’s coffee shop in Palo Alto, California. Bob’s coffee shop recently started accepting

bitcoin payments, by adding a bitcoin option to his point-of-sale system. The prices at

Bob’s Cafe are listed in the local currency (US dollars), but at the register, customers

have the option of paying in either dollars or bitcoin. Alice places her order for a cup

of coffee and Bob enters the transaction at the register. The point-of-sale system will

convert the total price from US dollars to bitcoins at the prevailing market rate and

display the prices in both currencies, as well as show a QR code containing a *payment*

*request* for this transaction (see Figure 2-2):

16 | Chapter 2: How Bitcoin Works

Total:

$1.50 USD

0.015 BTC

*Figure 2-2. Payment request QR code (Hint: Try to scan this!)*

The payment request QR code encodes the following URL, defined in BIP0021:

bitcoin:1GdK9UzpHBzqzX2A9JFP3Di4weBwqgmoQA?

amount=0.015&

label=Bob%27s%20Cafe&

message=Purchase%20at%20Bob%27s%20Cafe

Components of the URL

A bitcoin address: "1GdK9UzpHBzqzX2A9JFP3Di4weBwqgmoQA"

The payment amount: "0.015"

A label for the recipient address: "Bob's Cafe"

A description for the payment: "Purchase at Bob's Cafe"

Unlike a QR code that simply contains a destination bitcoin address,

a payment request is a QR-encoded URL that contains a destination

address, a payment amount, and a generic description such as

“Bob’s Cafe.” This allows a bitcoin wallet application to prefill the

information used to send the payment while showing a humanreadable

description to the user. You can scan the QR code with a

bitcoin wallet application to see what Alice would see.

Bob says, “That’s one-dollar-fifty, or fifteen millibits.”

Alice uses her smartphone to scan the barcode on display. Her smartphone shows a

payment of 0.0150 BTC to Bob’s Cafe and she selects Send to authorize the payment.

Within a few seconds (about the same amount of time as a credit card authorization),

Bob would see the transaction on the register, completing the transaction.

Transactions, Blocks, Mining, and the Blockchain | 17

In the following sections we will examine this transaction in more detail, see how Alice’s

wallet constructed it, how it was propagated across the network, how it was verified,

and finally, how Bob can spend that amount in subsequent transactions.

The bitcoin network can transact in fractional values, e.g., from millibitcoins

(1/1000th of a bitcoin) down to 1/100,000,000th of a bitcoin,

which is known as a satoshi. Throughout this book we’ll use the

term “bitcoin” to refer to any quantity of bitcoin currency, from the

smallest unit (1 satoshi) to the total number (21,000,000) of all bitcoins

that will ever be mined.

Bitcoin Transactions

In simple terms, a transaction tells the network that the owner of a number of bitcoins

has authorized the transfer of some of those bitcoins to another owner. The new owner

can now spend these bitcoins by creating another transaction that authorizes transfer

to another owner, and so on, in a chain of ownership.

Transactions are like lines in a double-entry bookkeeping ledger. In simple terms, each

transaction contains one or more “inputs,” which are debits against a bitcoin account.

On the other side of the transaction, there are one or more “outputs,” which are credits

added to a bitcoin account. The inputs and outputs (debits and credits) do not necessarily

add up to the same amount. Instead, outputs add up to slightly less than inputs

and the difference represents an implied “transaction fee,” which is a small payment

collected by the miner who includes the transaction in the ledger. A bitcoin transaction

is shown as a bookkeeping ledger entry in Figure 2-3.

The transaction also contains proof of ownership for each amount of bitcoin (inputs)

whose value is transferred, in the form of a digital signature from the owner, which can

be independently validated by anyone. In bitcoin terms, “spending” is signing a transaction

that transfers value from a previous transaction over to a new owner identified

by a bitcoin address.

*Transactions* move value from *transaction inputs* to *transaction outputs*.

An input is where the coin value is coming from, usually a

previous transaction’s output. A transaction output assigns a new

owner to the value by associating it with a key. The destination key is

called an *encumbrance*. It imposes a requirement for a signature for

the funds to be redeemed in future transactions. Outputs from one

transaction can be used as inputs in a new transaction, thus creating

a chain of ownership as the value is moved from address to address

(see Figure 2-4).

18 | Chapter 2: How Bitcoin Works

*Figure 2-3. Transaction as double-entry bookkeeping*

*Figure 2-4. A chain of transactions, where the output of one transaction is the input of*

*the next transaction*

Bitcoin Transactions | 19

Alice’s payment to Bob’s Cafe uses a previous transaction as its input. In the previous

chapter Alice received bitcoin from her friend Joe in return for cash. That transaction

has a number of bitcoins locked (encumbered) against Alice’s key. Her new transaction

to Bob’s Cafe references the previous transaction as an input and creates new outputs

to pay for the cup of coffee and receive change. The transactions form a chain, where

the inputs from the latest transaction correspond to outputs from previous transactions.

Alice’s key provides the signature that unlocks those previous transaction outputs,

thereby proving to the bitcoin network that she owns the funds. She attaches the payment

for coffee to Bob’s address, thereby “encumbering” that output with the requirement

that Bob produces a signature in order to spend that amount. This represents a

transfer of value between Alice and Bob. This chain of transactions, from Joe to Alice

to Bob, is illustrated in Figure 2-4.

Common Transaction Forms

The most common form of transaction is a simple payment from one address to another,

which often includes some “change” returned to the original owner. This type of transaction

has one input and two outputs and is shown in Figure 2-5.

*Figure 2-5. Most common transaction*

Another common form of transaction is one that aggregates several inputs into a single

output (see Figure 2-6). This represents the real-world equivalent of exchanging a pile

of coins and currency notes for a single larger note. Transactions like these are sometimes

generated by wallet applications to clean up lots of smaller amounts that were

received as change for payments.

20 | Chapter 2: How Bitcoin Works

*Figure 2-6. Transaction aggregating funds*

Finally, another transaction form that is seen often on the bitcoin ledger is a transaction

that distributes one input to multiple outputs representing multiple recipients (see

Figure 2-7). This type of transaction is sometimes used by commercial entities to distribute

funds, such as when processing payroll payments to multiple employees.

*Figure 2-7. Transaction distributing funds*

Constructing a Transaction

Alice’s wallet application contains all the logic for selecting appropriate inputs and outputs

to build a transaction to Alice’s specification. Alice only needs to specify a destination

and an amount and the rest happens in the wallet application without her seeing

the details. Importantly, a wallet application can construct transactions even if it is

completely offline. Like writing a check at home and later sending it to the bank in an

envelope, the transaction does not need to be constructed and signed while connected

to the bitcoin network. It only has to be sent to the network eventually for it to be

executed.

Constructing a Transaction | 21

Getting the Right Inputs

Alice’s wallet application will first have to find inputs that can pay for the amount she

wants to send to Bob. Most wallet applications keep a small database of “unspent transaction

outputs” that are locked (encumbered) with the wallet’s own keys. Therefore,

Alice’s wallet would contain a copy of the transaction output from Joe’s transaction,

which was created in exchange for cash (see “Getting Your First Bitcoins” on page 9). A

bitcoin wallet application that runs as a full-index client actually contains a copy of every

unspent output from every transaction in the blockchain. This allows a wallet to construct

transaction inputs as well as quickly verify incoming transactions as having correct

inputs. However, because a full-index client takes up a lot of disk space, most user

wallets run “lightweight” clients that track only the user’s own unspent outputs.

If the wallet application does not maintain a copy of unspent transaction outputs, it can

query the bitcoin network to retrieve this information, using a variety of APIs available

by different providers or by asking a full-index node using the bitcoin JSON RPC API.

Example 2-1 shows a RESTful API request, constructed as an HTTP GET command to

a specific URL. This URL will return all the unspent transaction outputs for an address,

giving any application the information it needs to construct transaction inputs for

spending. We use the simple command-line HTTP client *cURL* to retrieve the response.

*Example 2-1. Look up all the unspent outputs for Alice’s bitcoin address*

$ curl https://blockchain.info/unspent?active=1Cdid9KFAaatwczBwBttQcwXYCpvK8h7FK

*Example 2-2. Response to the lookup*

{

**"unspent\_outputs"**:[

{

**"tx\_hash"**:"186f9f998a5...2836dd734d2804fe65fa35779",

**"tx\_index"**:104810202,

**"tx\_output\_n"**: 0,

**"script"**:"76a9147f9b1a7fb68d60c536c2fd8aeaa53a8f3cc025a888ac",

**"value"**: 10000000,

**"value\_hex"**: "00989680",

**"confirmations"**:0

}

]

}

The response in Example 2-2 shows one unspent output (one that has not been redeemed

yet) under the ownership of Alice’s address 1Cdid9KFAaatwczBwBttQcw

XYCpvK8h7FK. The response includes the reference to the transaction in which this un‐

22 | Chapter 2: How Bitcoin Works

spent output is contained (the payment from Joe) and its value in satoshis, at 10 million,

equivalent to 0.10 bitcoin. With this information, Alice’s wallet application can construct

a transaction to transfer that value to new owner addresses.

View the transaction from Joe to Alice.

As you can see, Alice’s wallet contains enough bitcoins in a single unspent output to pay

for the cup of coffee. Had this not been the case, Alice’s wallet application might have

to “rummage” through a pile of smaller unspent outputs, like picking coins from a purse

until it could find enough to pay for coffee. In both cases, there might be a need to get

some change back, which we will see in the next section, as the wallet application creates

the transaction outputs (payments).

Creating the Outputs

A transaction output is created in the form of a script that creates an encumbrance on

the value and can only be redeemed by the introduction of a solution to the script. In

simpler terms, Alice’s transaction output will contain a script that says something like,

“This output is payable to whoever can present a signature from the key corresponding

to Bob’s public address.” Because only Bob has the wallet with the keys corresponding

to that address, only Bob’s wallet can present such a signature to redeem this output.

Alice will therefore “encumber” the output value with a demand for a signature from

Bob.

This transaction will also include a second output, because Alice’s funds are in the form

of a 0.10 BTC output, too much money for the 0.015 BTC cup of coffee. Alice will need

0.085 BTC in change. Alice’s change payment is created *by Alice’s wallet* in the very same

transaction as the payment to Bob. Essentially, Alice’s wallet breaks her funds into two

payments: one to Bob, and one back to herself. She can then use the change output in

a subsequent transaction, thus spending it later.

Finally, for the transaction to be processed by the network in a timely fashion, Alice’s

wallet application will add a small fee. This is not explicit in the transaction; it is implied

by the difference between inputs and outputs. If instead of taking 0.085 in change, Alice

creates only 0.0845 as the second output, there will be 0.0005 BTC (half a millibitcoin)

left over. The input’s 0.10 BTC is not fully spent with the two outputs, because they will

add up to less than 0.10. The resulting difference is the *transaction fee* that is collected

by the miner as a fee for including the transaction in a block and putting it on the

blockchain ledger.

Constructing a Transaction | 23

The resulting transaction can be seen using a blockchain explorer web application, as

shown in Figure 2-8.

*Figure 2-8. Alice’s transaction to Bob’s Cafe*

View the transaction from Alice to Bob’s Cafe.

Adding the Transaction to the Ledger

The transaction created by Alice’s wallet application is 258 bytes long and contains

everything necessary to confirm ownership of the funds and assign new owners. Now,

the transaction must be transmitted to the bitcoin network where it will become part

of the distributed ledger (the blockchain). In the next section we will see how a transaction

becomes part of a new block and how the block is “mined.” Finally, we will see

how the new block, once added to the blockchain, is increasingly trusted by the network

as more blocks are added.

Transmitting the transaction

Because the transaction contains all the information necessary to process, it does not

matter how or where it is transmitted to the bitcoin network. The bitcoin network is a

peer-to-peer network, with each bitcoin client participating by connecting to several

24 | Chapter 2: How Bitcoin Works

other bitcoin clients. The purpose of the bitcoin network is to propagate transactions

and blocks to all participants.

How it propagates

Alice’s wallet application can send the new transaction to any of the other bitcoin clients

it is connected to over any Internet connection: wired, WiFi, or mobile. Her bitcoin

wallet does not have to be connected to Bob’s bitcoin wallet directly and she does not

have to use the Internet connection offered by the cafe, though both those options are

possible, too. Any bitcoin network node (other client) that receives a valid transaction

it has not seen before will immediately forward it to other nodes to which it is connected.

Thus, the transaction rapidly propagates out across the peer-to-peer network, reaching

a large percentage of the nodes within a few seconds.

Bob’s view

If Bob’s bitcoin wallet application is directly connected to Alice’s wallet application, Bob’s

wallet application might be the first node to receive the transaction. However, even if

Alice’s wallet sends the transaction through other nodes, it will reach Bob’s wallet within

a few seconds. Bob’s wallet will immediately identify Alice’s transaction as an incoming

payment because it contains outputs redeemable by Bob’s keys. Bob’s wallet application

can also independently verify that the transaction is well formed, uses previously unspent

inputs, and contains sufficient transaction fees to be included in the next block.

At this point Bob can assume, with little risk, that the transaction will shortly be included

in a block and confirmed.

A common misconception about bitcoin transactions is that they

must be “confirmed” by waiting 10 minutes for a new block, or up to

60 minutes for a full six confirmations. Although confirmations ensure

the transaction has been accepted by the whole network, such a

delay is unnecessary for small-value items such as a cup of coffee. A

merchant may accept a valid small-value transaction with no confirmations,

with no more risk than a credit card payment made without

an ID or a signature, as merchants routinely accept today.

Bitcoin Mining

The transaction is now propagated on the bitcoin network. It does not become part of

the shared ledger (the *blockchain*) until it is verified and included in a block by a process

called *mining*. See Chapter 8 for a detailed explanation.

The bitcoin system of trust is based on computation. Transactions are bundled into

*blocks*, which require an enormous amount of computation to prove, but only a small

Bitcoin Mining | 25

amount of computation to verify as proven. The mining process serves two purposes

in bitcoin:

• Mining creates new bitcoins in each block, almost like a central bank printing new

money. The amount of bitcoin created per block is fixed and diminishes with time.

• Mining creates trust by ensuring that transactions are only confirmed if enough

computational power was devoted to the block that contains them. More blocks

mean more computation, which means more trust.

A good way to describe mining is like a giant competitive game of sudoku that resets

every time someone finds a solution and whose difficulty automatically adjusts so that

it takes approximately 10 minutes to find a solution. Imagine a giant sudoku puzzle,

several thousand rows and columns in size. If I show you a completed puzzle you can

verify it quite quickly. However, if the puzzle has a few squares filled and the rest are

empty, it takes a lot of work to solve! The difficulty of the sudoku can be adjusted by

changing its size (more or fewer rows and columns), but it can still be verified quite

easily even if it is very large. The “puzzle” used in bitcoin is based on a cryptographic

hash and exhibits similar characteristics: it is asymmetrically hard to solve but easy to

verify, and its difficulty can be adjusted.

In “Bitcoin Uses, Users, and Their Stories” on page 4, we introduced Jing, a computer

engineering student in Shanghai. Jing is participating in the bitcoin network as a miner.

Every 10 minutes or so, Jing joins thousands of other miners in a global race to find a

solution to a block of transactions. Finding such a solution, the so-called proof of work,

requires quadrillions of hashing operations per second across the entire bitcoin network.

The algorithm for proof of work involves repeatedly hashing the header of the

block and a random number with the SHA256 cryptographic algorithm until a solution

matching a predetermined pattern emerges. The first miner to find such a solution wins

the round of competition and publishes that block into the blockchain.

Jing started mining in 2010 using a very fast desktop computer to find a suitable proof

of work for new blocks. As more miners started joining the bitcoin network, the difficulty

of the problem increased rapidly. Soon, Jing and other miners upgraded to more

specialized hardware, such as high-end dedicated graphical processing units (GPUs)

cards such as those used in gaming desktops or consoles. At the time of this writing, the

difficulty is so high that it is profitable only to mine with application-specific integrated

circuits (ASIC), essentially hundreds of mining algorithms printed in hardware, running

in parallel on a single silicon chip. Jing also joined a “mining pool,” which much

like a lottery pool allows several participants to share their efforts and the rewards. Jing

now runs two USB-connected ASIC machines to mine for bitcoin 24 hours a day. He

pays his electricity costs by selling the bitcoin he is able to generate from mining, creating

some income from the profits. His computer runs a copy of bitcoind, the reference

bitcoin client, as a backend to his specialized mining software.

26 | Chapter 2: How Bitcoin Works

Mining Transactions in Blocks

A transaction transmitted across the network is not verified until it becomes part of the

global distributed ledger, the blockchain. Every 10 minutes on average, miners generate

a new block that contains all the transactions since the last block. New transactions are

constantly flowing into the network from user wallets and other applications. As these

are seen by the bitcoin network nodes, they get added to a temporary pool of unverified

transactions maintained by each node. As miners build a new block, they add unverified

transactions from this pool to a new block and then attempt to solve a very hard problem

(a.k.a., proof of work) to prove the validity of that new block. The process of mining is

explained in detail in “Introduction” on page 173.

Transactions are added to the new block, prioritized by the highest-fee transactions first

and a few other criteria. Each miner starts the process of mining a new block of transactions

as soon as he receives the previous block from the network, knowing he has lost

that previous round of competition. He immediately creates a new block, fills it with

transactions and the fingerprint of the previous block, and starts calculating the proof

of work for the new block. Each miner includes a special transaction in his block, one

that pays his own bitcoin address a reward of newly created bitcoins (currently 25 BTC

per block). If he finds a solution that makes that block valid, he “wins” this reward

because his successful block is added to the global blockchain and the reward transaction

he included becomes spendable. Jing, who participates in a mining pool, has set up his

software to create new blocks that assign the reward to a pool address. From there, a

share of the reward is distributed to Jing and other miners in proportion to the amount

of work they contributed in the last round.

Alice’s transaction was picked up by the network and included in the pool of unverified

transactions. Because it had sufficient fees, it was included in a new block generated by

Jing’s mining pool. Approximately five minutes after the transaction was first transmitted

by Alice’s wallet, Jing’s ASIC miner found a solution for the block and published

it as block #277316, containing 419 other transactions. Jing’s ASIC miner published the

new block on the bitcoin network, where other miners validated it and started the race

to generate the next block.

You can see the block that includes Alice’s transaction.

A few minutes later, a new block, #277317, is mined by another miner. Because this new

block is based on the previous block (#277316) that contained Alice’s transaction, it

added even more computation on top of that block, thereby strengthening the trust in

those transactions. The block containing Alice’s transaction is counted as one “confirmation”

of that transaction. Each block mined on top of the one containing the transaction

is an additional confirmation. As the blocks pile on top of each other, it becomes

exponentially harder to reverse the transaction, thereby making it more and more trusted

by the network.

Mining Transactions in Blocks | 27

In the diagram in Figure 2-9 we can see block #277316, which contains Alice’s transaction.

Below it are 277,316 blocks (including block #0), linked to each other in a chain

of blocks (blockchain) all the way back to block #0, known as the *genesis block*. Over

time, as the “height” in blocks increases, so does the computation difficulty for each

block and the chain as a whole. The blocks mined after the one that contains Alice’s

transaction act as further assurance, as they pile on more computation in a longer and

longer chain. By convention, any block with more than six confirmations is considered

irrevocable, because it would require an immense amount of computation to invalidate

and recalculate six blocks. We will examine the process of mining and the way it builds

trust in more detail in Chapter 8.

*Figure 2-9. Alice’s transaction included in block #277316*

Spending the Transaction

Now that Alice’s transaction has been embedded in the blockchain as part of a block, it

is part of the distributed ledger of bitcoin and visible to all bitcoin applications. Each

bitcoin client can independently verify the transaction as valid and spendable. Fullindex

clients can track the source of the funds from the moment the bitcoins were first

generated in a block, incrementally from transaction to transaction, until they reach

Bob’s address. Lightweight clients can do what is called a simplified payment verification

(see “Simplified Payment Verification (SPV) Nodes” on page 147) by confirming that the

transaction is in the blockchain and has several blocks mined after it, thus providing

assurance that the network accepts it as valid.

28 | Chapter 2: How Bitcoin Works

Bob can now spend the output from this and other transactions, by creating his own

transactions that reference these outputs as their inputs and assign them new ownership.

For example, Bob can pay a contractor or supplier by transferring value from Alice’s

coffee cup payment to these new owners. Most likely, Bob’s bitcoin software will aggregate

many small payments into a larger payment, perhaps concentrating all the day’s

bitcoin revenue into a single transaction. This would move the various payments into

a single address, used as the store’s general “checking” account. For a diagram of an

aggregating transaction, see Figure 2-6.

As Bob spends the payments received from Alice and other customers, he extends the

chain of transactions, which in turn are added to the global blockchain ledger for all to

see and trust. Let’s assume that Bob pays his web designer Gopesh in Bangalore for a

new website page. Now the chain of transactions will look like Figure 2-10.

*Figure 2-10. Alice’s transaction as part of a transaction chain from Joe to Gopesh*

Spending the Transaction | 29

CHAPTER 3

The Bitcoin Client

Bitcoin Core: The Reference Implementation

You can download the reference client *Bitcoin Core*, also known as the “Satoshi client,”

from bitcoin.org. The reference client implements all aspects of the bitcoin system,

including wallets, a transaction verification engine with a full copy of the entire transaction

ledger (blockchain), and a full network node in the peer-to-peer bitcoin network.

On Bitcoin’s Choose Your Wallet page, select Bitcoin Core to download the reference

client. Depending on your operating system, you will download an executable installer.

For Windows, this is either a ZIP archive or an .exe executable. For Mac OS it is a .dmg

disk image. Linux versions include a PPA package for Ubuntu or a tar.gz archive. The

bitcoin.org page that lists recommended bitcoin clients is shown in Figure 3-1.

*Figure 3-1. Choosing a bitcoin client at bitcoin.org*

Running Bitcoin Core for the First Time

If you download an installable package, such as an .exe, .dmg, or PPA, you can install

it the same way as any application on your operating system. For Windows, run the .exe

31

and follow the step-by-step instructions. For Mac OS, launch the .dmg and drag the

Bitcoin-QT icon into your *Applications* folder. For Ubuntu, double-click the PPA in

your File Explorer and it will open the package manager to install the package. Once

you have completed installation you should have a new application called Bitcoin-Qt

in your application list. Double-click the icon to start the bitcoin client.

The first time you run Bitcoin Core it will start downloading the blockchain, a process

that might take several days (see Figure 3-2). Leave it running in the background until

it displays “Synchronized” and no longer shows “out of sync” next to the balance.

*Figure 3-2. Bitcoin Core screen during the blockchain initialization*

Bitcoin Core keeps a full copy of the transaction ledger (blockchain),

with every transaction that has ever occurred on the bitcoin

network since its inception in 2009. This dataset is several gigabytes

in size (approximately 16 GB in late 2013) and is downloaded incrementally

over several days. The client will not be able to process

transactions or update account balances until the full blockchain dataset

is downloaded. During that time, the client will display “out of

sync” next to the account balances and show “Synchronizing” in the

footer. Make sure you have enough disk space, bandwidth, and time

to complete the initial synchronization.

32 | Chapter 3: The Bitcoin Client

Compiling Bitcoin Core from the Source Code

For developers, there is also the option to download the full source code as a ZIP archive

or by cloning the authoritative source repository from GitHub. On the GitHub bitcoin

page, select Download ZIP from the sidebar. Alternatively, use the git command line to

create a local copy of the source code on your system. In the following example, we are

cloning the source code from a Unix-like command line, in Linux or Mac OS:

$ git clone https://github.com/bitcoin/bitcoin.git

Cloning into 'bitcoin'...

remote: Counting objects: 31864, done.

remote: Compressing objects: 100% (12007/12007), done.

remote: Total 31864 (delta 24480), reused 26530 (delta 19621)

Receiving objects: 100% (31864/31864), 18.47 MiB | 119 KiB/s, done.

Resolving deltas: 100% (24480/24480), done.

$

The instructions and resulting output might vary from version to

version. Follow the documentation that comes with the code even if

it differs from the instructions you see here, and don’t be surprised if

the output displayed on your screen is slightly different from the

examples here.

When the git cloning operation has completed, you will have a complete local copy of

the source code repository in the directory *bitcoin*. Change to this directory by typing

cd bitcoin at the prompt:

$ cd bitcoin

By default, the local copy will be synchronized with the most recent code, which might

be an unstable or beta version of bitcoin. Before compiling the code, select a specific

version by checking out a release *tag*. This will synchronize the local copy with a specific

snapshot of the code repository identified by a keyword tag. Tags are used by the developers

to mark specific releases of the code by version number. First, to find the available

tags, we use the git tag command:

$ git tag

v0.1.5

v0.1.6test1

v0.2.0

v0.2.10

v0.2.11

v0.2.12

[... many more tags ...]

v0.8.4rc2

v0.8.5

v0.8.6

Bitcoin Core: The Reference Implementation | 33

v0.8.6rc1

v0.9.0rc1

The list of tags shows all the released versions of bitcoin. By convention, *release candidates*,

which are intended for testing, have the suffix “rc”. Stable releases that can be run

on production systems have no suffix. From the preceding list, select the highest version

release, which at this writing was v0.9.0rc1. To synchronize the local code with this

version, use the git checkout command:

$ git checkout v0.9.0rc1

Note: checking out 'v0.9.0rc1'.

HEAD is now at 15ec451... Merge pull request #3605

$

The source code includes documentation, which can be found in a number of files.

Review the main documentation located in *README.md* in the bitcoin directory by

typing more README.md at the prompt and using the space bar to progress to the next

page. In this chapter, we will build the command-line bitcoin client, also known as

bitcoind on Linux. Review the instructions for compiling the bitcoind command-line

client on your platform by typing more doc/build-unix.md. Alternative instructions

for Mac OS X and Windows can be found in the *doc* directory, as *build-osx.md* or *buildmsw.*

*md*, respectively.

Carefully review the build prerequisites, which are in the first part of the build documentation.

These are libraries that must be present on your system before you can begin

to compile bitcoin. If these prerequisites are missing, the build process will fail with an

error. If this happens because you missed a prerequisite, you can install it and then

resume the build process from where you left off. Assuming the prerequisites are installed,

you start the build process by generating a set of build scripts using the *autogen.*

*sh* script.

The Bitcoin Core build process was changed to use the autogen/

configure/make system starting with version 0.9. Older versions use

a simple Makefile and work slightly differently from the following

example. Follow the instructions for the version you want to compile.

The autogen/configure/make introduced in 0.9 is likely to be the

build system used for all future versions of the code and is the system

demonstrated in the following examples.

$ ./autogen.sh

configure.ac:12: installing `src/build-aux/config.guess'

configure.ac:12: installing `src/build-aux/config.sub'

configure.ac:37: installing `src/build-aux/install-sh'

configure.ac:37: installing `src/build-aux/missing'

src/Makefile.am: installing `src/build-aux/depcomp'

$

34 | Chapter 3: The Bitcoin Client

The *autogen.sh* script creates a set of automatic configuration scripts that will interrogate

your system to discover the correct settings and ensure you have all the necessary libraries

to compile the code. The most important of these is the configure script that

offers a number of different options to customize the build process. Type ./configure

--help to see the various options:

$ ./configure --help

`configure' configures Bitcoin Core 0.9.0 to adapt to many kinds of systems.

Usage: ./configure [OPTION]... [VAR=VALUE]...

To assign environment variables (e.g., CC, CFLAGS...), specify them as

VAR=VALUE. See below for descriptions of some of the useful variables.

Defaults for the options are specified in brackets.

Configuration:

-h, --help display this help and exit

--help=short display options specific to this package

--help=recursive display the short help of all the included packages

-V, --version display version information and exit

[... many more options and variables are displayed below ...]

Optional Features:

--disable-option-checking ignore unrecognized --enable/--with options

--disable-FEATURE do not include FEATURE (same as --enable-FEATURE=no)

--enable-FEATURE[=ARG] include FEATURE [ARG=yes]

[... more options ...]

Use these variables to override the choices made by `configure' or to help

it to find libraries and programs with nonstandard names/locations.

Report bugs to <info@bitcoin.org>.

$

The configure script allows you to enable or disable certain features of bitcoind through

the use of the --enable-FEATURE and --disable-FEATURE flags, where FEATURE is replaced

by the feature name, as listed in the help output. In this chapter, we will build

the bitcoind client with all the default features. We won’t be using the configuration

flags, but you should review them to understand what optional features are part of the

client. Next, run the configure script to automatically discover all the necessary libraries

and create a customized build script for your system:

$ ./configure

checking build system type... x86\_64-unknown-linux-gnu

checking host system type... x86\_64-unknown-linux-gnu

Bitcoin Core: The Reference Implementation | 35

checking for a BSD-compatible install... /usr/bin/install -c

checking whether build environment is sane... yes

checking for a thread-safe mkdir -p... /bin/mkdir -p

checking for gawk... no

checking for mawk... mawk

checking whether make sets $(MAKE)... yes

[... many more system features are tested ...]

configure: creating ./config.status

config.status: creating Makefile

config.status: creating src/Makefile

config.status: creating src/test/Makefile

config.status: creating src/qt/Makefile

config.status: creating src/qt/test/Makefile

config.status: creating share/setup.nsi

config.status: creating share/qt/Info.plist

config.status: creating qa/pull-tester/run-bitcoind-for-test.sh

config.status: creating qa/pull-tester/build-tests.sh

config.status: creating src/bitcoin-config.h

config.status: executing depfiles commands

$

If all goes well, the configure command will end by creating the customized build

scripts that will allow us to compile bitcoind. If there are any missing libraries or errors,

the configure command will terminate with an error instead of creating the build

scripts. If an error occurs, it is most likely because of a missing or incompatible library.

Review the build documentation again and make sure you install the missing prerequisites.

Then run configure again and see if that fixes the error. Next, you will compile

the source code, a process that can take up to an hour to complete. During the compilation

process you should see output every few seconds or every few minutes, or an

error if something goes wrong. The compilation process can be resumed at any time if

interrupted. Type make to start compiling:

$ make

Making all in src

make[1]: Entering directory `/home/ubuntu/bitcoin/src'

make all-recursive

make[2]: Entering directory `/home/ubuntu/bitcoin/src'

Making all in .

make[3]: Entering directory `/home/ubuntu/bitcoin/src'

CXX addrman.o

CXX alert.o

CXX rpcserver.o

CXX bloom.o

CXX chainparams.o

[... many more compilation messages follow ...]

CXX test\_bitcoin-wallet\_tests.o

CXX test\_bitcoin-rpc\_wallet\_tests.o

36 | Chapter 3: The Bitcoin Client

CXXLD test\_bitcoin

make[4]: Leaving directory `/home/ubuntu/bitcoin/src/test'

make[3]: Leaving directory `/home/ubuntu/bitcoin/src/test'

make[2]: Leaving directory `/home/ubuntu/bitcoin/src'

make[1]: Leaving directory `/home/ubuntu/bitcoin/src'

make[1]: Entering directory `/home/ubuntu/bitcoin'

make[1]: Nothing to be done for `all-am'.

make[1]: Leaving directory `/home/ubuntu/bitcoin'

$

If all goes well, bitcoind is now compiled. The final step is to install the bitcoind executable

into the system path using the make command:

$ sudo make install

Making install in src

Making install in .

/bin/mkdir -p '/usr/local/bin'

/usr/bin/install -c bitcoind bitcoin-cli '/usr/local/bin'

Making install in test

make install-am

/bin/mkdir -p '/usr/local/bin'

/usr/bin/install -c test\_bitcoin '/usr/local/bin'

$

You can confirm that bitcoin is correctly installed by asking the system for the path of

the two executables, as follows:

$ which bitcoind

/usr/local/bin/bitcoind

$ which bitcoin-cli

/usr/local/bin/bitcoin-cli

The default installation of bitcoind puts it in */usr/local/bin*. When you first run bitcoind,

it will remind you to create a configuration file with a strong password for the JSONRPC

interface. Run bitcoind by typing bitcoind into the terminal:

$ bitcoind

Error: To use the "-server" option, you must set a rpcpassword in the configuration

file:

/home/ubuntu/.bitcoin/bitcoin.conf

It is recommended you use the following random password:

rpcuser=bitcoinrpc

rpcpassword=2XA4DuKNCbtZXsBQRRNDEwEY2nM6M4H9Tx5dFjoAVVbK

(you do not need to remember this password)

The username and password MUST NOT be the same.

If the file does not exist, create it with owner-readable-only file permissions.

It is also recommended to set alertnotify so you are notified of problems;

for example: alertnotify=echo %s | mail -s "Bitcoin Alert" admin@foo.com

Edit the configuration file in your preferred editor and set the parameters, replacing the

password with a strong password as recommended by bitcoind. Do *not* use the password

Bitcoin Core: The Reference Implementation | 37

shown here. Create a file inside the *.bitcoin* directory so that it is named *.bitcoin/*

*bitcoin.conf* and enter a username and password:

rpcuser=bitcoinrpc

rpcpassword=2XA4DuKNCbtZXsBQRRNDEwEY2nM6M4H9Tx5dFjoAVVbK

While you’re editing this configuration file, you might want to set a few other options,

such as txindex (see “Transaction Database Index and txindex Option” on page 47). For

a full listing of the available options, type bitcoind --help.

Now, run the Bitcoin Core client. The first time you run it, it will rebuild the bitcoin

blockchain by downloading all the blocks. This is a multigigabyte file and will take an

average of two days to download in full. You can shorten the blockchain initialization

time by downloading a partial copy of the blockchain using a BitTorrent client from

SourceForge.

Run bitcoind in the background with the option -daemon:

$ bitcoind -daemon

Bitcoin version v0.9.0rc1-beta (2014-01-31 09:30:15 +0100)

Using OpenSSL version OpenSSL 1.0.1c 10 May 2012

Default data directory /home/bitcoin/.bitcoin

Using data directory /bitcoin/

Using at most 4 connections (1024 file descriptors available)

init message: Verifying wallet...

dbenv.open LogDir=/bitcoin/database ErrorFile=/bitcoin/db.log

Bound to [::]:8333

Bound to 0.0.0.0:8333

init message: Loading block index...

Opening LevelDB in /bitcoin/blocks/index

Opened LevelDB successfully

Opening LevelDB in /bitcoin/chainstate

Opened LevelDB successfully

[... more startup messages ...]

Using Bitcoin Core’s JSON-RPC API from the Command Line

The Bitcoin Core client implements a JSON-RPC interface that can also be accessed

using the command-line helper bitcoin-cli. The command line allows us to experiment

interactively with the capabilities that are also available programmatically via the

API. To start, invoke the help command to see a list of the available bitcoin RPC commands:

$ bitcoin-cli help

addmultisigaddress nrequired ["key",...] ( "account" )

addnode "node" "add|remove|onetry"

backupwallet "destination"

createmultisig nrequired ["key",...]

38 | Chapter 3: The Bitcoin Client

createrawtransaction [{"txid":"id","vout":n},...] {"address":amount,...}

decoderawtransaction "hexstring"

decodescript "hex"

dumpprivkey "bitcoinaddress"

dumpwallet "filename"

getaccount "bitcoinaddress"

getaccountaddress "account"

getaddednodeinfo dns ( "node" )

getaddressesbyaccount "account"

getbalance ( "account" minconf )

getbestblockhash

getblock "hash" ( verbose )

getblockchaininfo

getblockcount

getblockhash index

getblocktemplate ( "jsonrequestobject" )

getconnectioncount

getdifficulty

getgenerate

gethashespersec

getinfo

getmininginfo

getnettotals

getnetworkhashps ( blocks height )

getnetworkinfo

getnewaddress ( "account" )

getpeerinfo

getrawchangeaddress

getrawmempool ( verbose )

getrawtransaction "txid" ( verbose )

getreceivedbyaccount "account" ( minconf )

getreceivedbyaddress "bitcoinaddress" ( minconf )

gettransaction "txid"

gettxout "txid" n ( includemempool )

gettxoutsetinfo

getunconfirmedbalance

getwalletinfo

getwork ( "data" )

help ( "command" )

importprivkey "bitcoinprivkey" ( "label" rescan )

importwallet "filename"

keypoolrefill ( newsize )

listaccounts ( minconf )

listaddressgroupings

listlockunspent

listreceivedbyaccount ( minconf includeempty )

listreceivedbyaddress ( minconf includeempty )

listsinceblock ( "blockhash" target-confirmations )

listtransactions ( "account" count from )

listunspent ( minconf maxconf ["address",...] )

lockunspent unlock [{"txid":"txid","vout":n},...]

move "fromaccount" "toaccount" amount ( minconf "comment" )

Using Bitcoin Core’s JSON-RPC API from the Command Line | 39

ping

sendfrom "fromaccount" "tobitcoinaddress" amount ( minconf "comment" "commentto"

)

sendmany "fromaccount" {"address":amount,...} ( minconf "comment" )

sendrawtransaction "hexstring" ( allowhighfees )

sendtoaddress "bitcoinaddress" amount ( "comment" "comment-to" )

setaccount "bitcoinaddress" "account"

setgenerate generate ( genproclimit )

settxfee amount

signmessage "bitcoinaddress" "message"

signrawtransaction "hexstring" ( [{"txid":"id","vout":n,"scriptPub-

Key":"hex","redeemScript":"hex"},...] ["privatekey1",...] sighashtype )

stop

submitblock "hexdata" ( "jsonparametersobject" )

validateaddress "bitcoinaddress"

verifychain ( checklevel numblocks )

verifymessage "bitcoinaddress" "signature" "message"

walletlock

walletpassphrase "passphrase" timeout

walletpassphrasechange "oldpassphrase" "newpassphrase"

Getting Information on the Bitcoin Core Client Status

Commands: getinfo

Bitcoin’s getinfo RPC command displays basic information about the status of the

bitcoin network node, the wallet, and the blockchain database. Use bitcoin-cli to run

it:

$ bitcoin-cli getinfo

{

**"version"** : 90000,

**"protocolversion"** : 70002,

**"walletversion"** : 60000,

**"balance"** : 0.00000000,

**"blocks"** : 286216,

**"timeoffset"** : -72,

**"connections"** : 4,

**"proxy"** : "",

**"difficulty"** : 2621404453.06461525,

**"testnet"** : **false**,

**"keypoololdest"** : 1374553827,

**"keypoolsize"** : 101,

**"paytxfee"** : 0.00000000,

**"errors"** : ""

}

The data is returned in JavaScript Object Notation (JSON), a format that can easily be

“consumed” by all programming languages but is also quite human-readable. Among

this data we see the version numbers for the bitcoin software client (90000), protocol

(70002), and wallet (60000). We see the current balance contained in the wallet, which

40 | Chapter 3: The Bitcoin Client

is zero. We see the current block height, showing us how many blocks are known to this

client (286216). We also see various statistics about the bitcoin network and the settings

related to this client. We will explore these settings in more detail in the rest of this

chapter.

It will take some time, perhaps more than a day, for the bitcoind client

to “catch up” to the current blockchain height as it downloads blocks

from other bitcoin clients. You can check its progress using getinfo

to see the number of known blocks.

Wallet Setup and Encryption

Commands: encryptwallet, walletpassphrase

Before you proceed with creating keys and other commands, you should first encrypt

the wallet with a password. For this example, you will use the encryptwallet command

with the password “foo”. Obviously, replace “foo” with a strong and complex password!

$ bitcoin-cli encryptwallet foo

wallet encrypted; Bitcoin server stopping, restart to run with encrypted wallet.

The keypool has been flushed, you need to make a new backup.

$

You can verify the wallet has been encrypted by running getinfo again. This time you

will notice a new entry called unlocked\_until. This is a counter showing how long the

wallet decryption password will be stored in memory, keeping the wallet unlocked. At

first this will be set to zero, meaning the wallet is locked:

$ bitcoin-cli getinfo

{

**"version"** : 90000,

#[... other information...]

**"unlocked\_until"** : 0,

**"errors"** : ""

}

$

To unlock the wallet, issue the walletpassphrase command, which takes two parameters—

the password and a number of seconds until the wallet is locked again automatically

(a time counter):

$ bitcoin-cli walletpassphrase foo 360

$

You can confirm the wallet is unlocked and see the timeout by running getinfo again:

Using Bitcoin Core’s JSON-RPC API from the Command Line | 41

$ bitcoin-cli getinfo

{

**"version"** : 90000,

#[... other information ...]

**"unlocked\_until"** : 1392580909,

**"errors"** : ""

}

Wallet Backup, Plain-text Dump, and Restore

Commands: backupwallet, importwallet, dumpwallet

Next, we will practice creating a wallet backup file and then restoring the wallet from

the backup file. Use the backupwallet command to back up, providing the filename as

the parameter. Here we back up the wallet to the file *wallet.backup*:

$ bitcoin-cli backupwallet wallet.backup

$

Now, to restore the backup file, use the importwallet command. If your wallet is locked,

you will need to unlock it first (see walletpassphrase in the preceding section) in order

to import the backup file:

$ bitcoin-cli importwallet wallet.backup

$

The dumpwallet command can be used to dump the wallet into a text file that is humanreadable:

$ bitcoin-cli dumpwallet wallet.txt

$ more wallet.txt

# Wallet dump created by Bitcoin v0.9.0rc1-beta (2014-01-31 09:30:15 +0100)

# \* Created on 2014-02- 8dT20:34:55Z

# \* Best block at time of backup was 286234

(0000000000000000f74f0bc9d3c186267bc45c7b91c49a0386538ac24c0d3a44),

# mined on 2014-02- 8dT20:24:01Z

KzTg2wn6Z8s7ai5NA9MVX4vstHRsqP26QKJCzLg4JvFrp6mMaGB9 2013-07- 4dT04:30:27Z

change=1 # addr=16pJ6XkwSQv5ma5FSXMRPaXEYrENCEg47F

Kz3dVz7R6mUpXzdZy4gJEVZxXJwA15f198eVui4CUivXotzLBDKY 2013-07- 4dT04:30:27Z

change=1 # addr=17oJds8kaN8LP8kuAkWTco6ZM7BGXFC3gk

[... many more keys ...]

$

Wallet Addresses and Receiving Transactions

Commands: getnewaddress, getreceivedbyaddress, listtransactions, getaddressesbyaccount,

getbalance

42 | Chapter 3: The Bitcoin Client

The bitcoin reference client maintains a pool of addresses, the size of which is displayed

by keypoolsize when you use the command getinfo. These addresses are generated

automatically and can then be used as public receiving addresses or change addresses.

To get one of these addresses, use the getnewaddress command:

$ bitcoin-cli getnewaddress

1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL

Now, we can use this address to send a small amount of bitcoin to our bitcoind wallet

from an external wallet (assuming you have some bitcoin in an exchange, web wallet,

or other bitcoind wallet held elsewhere). For this example, we will send 50 millibits

(0.050 bitcoin) to the preceding address.

We can now query the bitcoind client for the amount received by this address, and

specify how many confirmations are required before an amount is counted in that balance.

For this example, we will specify zero confirmations. A few seconds after sending

the bitcoin from another wallet, we will see it reflected in the wallet. We use getrecei

vedbyaddress with the address and the number of confirmations set to zero (0):

$ bitcoin-cli getreceivedbyaddress 1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL 0

0.05000000

If we omit the zero from the end of this command, we will only see the amounts that

have at least minconf confirmations, where minconf is the setting for the minimum

number of confirmations before a transaction is listed in the balance. The minconf

setting is specified in the bitcoind configuration file. Because the transaction sending

this bitcoin was only sent in the last few seconds, it has still not confirmed and therefore

we will see it list a zero balance:

$ bitcoin-cli getreceivedbyaddress 1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL

0.00000000

The transactions received by the entire wallet can also be displayed using the listtran

sactions command:

$ bitcoin-cli listtransactions

[

{

**"account"** : "",

**"address"** : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

**"category"** : "receive",

**"amount"** : 0.05000000,

**"confirmations"** : 0,

**"txid"** : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309ac

bae2c14ae3",

**"time"** : 1392660908,

**"timereceived"** : 1392660908

}

]

Using Bitcoin Core’s JSON-RPC API from the Command Line | 43

We can list all addresses in the entire wallet using the getaddressesbyaccount command:

$ bitcoin-cli getaddressesbyaccount ""

[

"1LQoTPYy1TyERbNV4zZbhEmgyfAipC6eqL",

"17vrg8uwMQUibkvS2ECRX4zpcVJ78iFaZS",

"1FvRHWhHBBZA8cGRRsGiAeqEzUmjJkJQWR",

"1NVJK3JsL41BF1KyxrUyJW5XHjunjfp2jz",

"14MZqqzCxjc99M5ipsQSRfieT7qPZcM7Df",

"1BhrGvtKFjTAhGdPGbrEwP3xvFjkJBuFCa",

"15nem8CX91XtQE8B1Hdv97jE8X44H3DQMT",

"1Q3q6taTsUiv3mMemEuQQJ9sGLEGaSjo81",

"1HoSiTg8sb16oE6SrmazQEwcGEv8obv9ns",

"13fE8BGhBvnoy68yZKuWJ2hheYKovSDjqM",

"1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

"1KHUmVfCJteJ21LmRXHSpPoe23rXKifAb2",

"1LqJZz1D9yHxG4cLkdujnqG5jNNGmPeAMD"

]

Finally, the command getbalance will show the total balance of the wallet, adding up

all transactions confirmed with at least minconf confirmations:

$ bitcoin-cli getbalance

0.05000000

If the transaction has not yet confirmed, the balance returned by

getbalance will be zero. The configuration option “minconf” determines

the minimum number of confirmations that are required before

a transaction shows in the balance.

Exploring and Decoding Transactions

Commands: gettransaction, getrawtransaction, decoderawtransaction

We’ll now explore the incoming transaction that was listed previously using the get

transaction command. We can retrieve a transaction by its transaction hash, shown

at txid earlier, with the gettransaction command:

$ bitcoin-cli gettransaction

9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c14ae3

{

**"amount"** : 0.05000000,

**"confirmations"** : 0,

**"txid"** : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c14ae3",

**"time"** : 1392660908,

**"timereceived"** : 1392660908,

**"details"** : [

44 | Chapter 3: The Bitcoin Client

{

**"account"** : "",

**"address"** : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

**"category"** : "receive",

**"amount"** : 0.05000000

}

]

}

Transaction IDs are not authoritative until a transaction has been

confirmed. Absence of a transaction hash in the blockchain does not

mean the transaction was not processed. This is known as “transaction

malleability,” because transaction hashes can be modified prior

to confirmation in a block. After confirmation, the txid is immutable

and authoritative.

The transaction form shown with the command gettransaction is the simplified form.

To retrieve the full transaction code and decode it, we will use two commands: getraw

transaction and decoderawtransaction. First, getrawtransaction takes the *transaction*

*hash (txid)* as a parameter and returns the full transaction as a “raw” hex string,

exactly as it exists on the bitcoin network:

$ bitcoin-cli getrawtransaction 9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc6↵

6c309acbae2c14ae30100000001d717279515f88e2f56ce4e8a31e2ae3e9f00ba1d0add648e80c4↵

80ea22e0c7d3000000008b483045022100a4ebbeec83225dedead659bbde7da3d026c8b8e12e61a↵

2df0dd0758e227383b302203301768ef878007e9ef7c304f70ffaf1f2c975b192d34c5b9b2ac1bd↵

193dfba2014104793ac8a58ea751f9710e39aad2e296cc14daa44fa59248be58ede65e4c4b884ac↵

5b5b6dede05ba84727e34c8fd3ee1d6929d7a44b6e111d41cc79e05dbfe5ceaffffffff02404b4c↵

00000000001976a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac1f312906000000001↵

976a914107b7086b31518935c8d28703d66d09b3623134388ac00000000

To decode this hex string, use the decoderawtransaction command. Copy and paste

the hex as the first parameter of decoderawtransaction to get the full contents interpreted

as a JSON data structure (for formatting reasons the hex string is shortened in

the following example):

$ bitcoin-cli decoderawtransaction 0100000001d717...388ac00000000

{

"txid" : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c14ae3",

"version" : 1,

"locktime" : 0,

"vin" : [

{

"txid" : "d3c7e022ea80c4808e64dd0a1dba009f3eaee2318a4ece562f8ef815↵

952717d7",

"vout" : 0,

"scriptSig" : {

"asm" : "3045022100a4ebbeec83225dedead659bbde7da3d026c8b8e12e↵

Using Bitcoin Core’s JSON-RPC API from the Command Line | 45

61a2df0dd0758e227383b302203301768ef878007e9ef7c304f70ffaf1f2c975b192d34c5b9b2↵

ac1bd193dfba20104793ac8a58ea751f9710e39aad2e296cc14daa44fa59248be58ede65e4c4b↵

884ac5b5b6dede05ba84727e34c8fd3ee1d6929d7a44b6e111d41cc79e05dbfe5cea",

"hex": "483045022100a4ebbeec83225dedead659bbde7da3d026c8b8e1↵

2e61a2df0dd0758e227383b302203301768ef878007e9ef7c304f70ffaf1f2c975b192d34c5b9↵

b2ac1bd193dfba2014104793ac8a58ea751f9710e39aad2e296cc14daa44fa59248be58ede65e↵

4c4b884ac5b5b6dede05ba84727e34c8fd3ee1d6929d7a44b6e111d41cc79e05dbfe5cea"

},

"sequence" : 4294967295

}

],

"vout" : [

{

"value" : 0.05000000,

"n" : 0,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 07bdb518fa2e6089fd810235cf1100c9c↵

13d1fd2 OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL"

]

}

},

{

"value" : 1.03362847,

"n" : 1,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 107b7086b31518935c8d28703d66d09b36↵

231343 OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a914107b7086b31518935c8d28703d66d09b3623134388ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"12W9goQ3P7Waw5JH8fRVs1e2rVAKoGnvoy"

]

}

}

]

}

The transaction decode shows all the components of this transaction, including the

transaction inputs and outputs. In this case we see that the transaction that credited our

new address with 50 millibits used one input and generated two outputs. The input to

this transaction was the output from a previously confirmed transaction (shown as the

vin txid starting with d3c7). The two outputs correspond to the 50 millibit credit and

an output with change back to the sender.

46 | Chapter 3: The Bitcoin Client

We can further explore the blockchain by examining the previous transaction referenced

by its txid in this transaction using the same commands (e.g., gettransaction). Jumping

from transaction to transaction we can follow a chain of transactions back as the

coins are transmitted from owner address to owner address.

Once the transaction we received has been confirmed by inclusion in a block, the

gettransaction command will return additional information, showing the *block hash*

*(identifier)* in which the transaction was included:

$ bitcoin-cli gettransaction 9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66↵

c309acbae2c14ae3

{

"amount" : 0.05000000,

"confirmations" : 1,

"blockhash" : "000000000000000051d2e759c63a26e247f185ecb7926ed7a6624bc31c↵

2a717b",

"blockindex" : 18,

"blocktime" : 1392660808,

"txid" : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c14ae3",

"time" : 1392660908,

"timereceived" : 1392660908,

"details" : [

{

"account" : "",

"address" : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

"category" : "receive",

"amount" : 0.05000000

}

]

}

Here, we see the new information in the entries blockhash (the hash of the block in

which the transaction was included), and blockindex with value 18 (indicating that our

transaction was the 18th transaction in that block).

Transaction Database Index and txindex Option

By default, Bitcoin Core builds a database containing *only* the transactions related to

the user’s wallet. If you want to be able to access *any* transaction with commands like

gettransaction, you need to configure Bitcoin Core to build a complete transaction

index, which can be achieved with the txindex option. Set txindex=1 in the Bitcoin

Core configuration file (usually found in your home directory under *.bitcoin/*

*bitcoin.conf*). Once you change this parameter, you need to restart bitcoind and wait for

it to rebuild the index.

Using Bitcoin Core’s JSON-RPC API from the Command Line | 47

Exploring Blocks

Commands: getblock, getblockhash

Now that we know which block our transaction was included in, we can query that

block. We use the getblock command with the block hash as the parameter:

$ bitcoin-cli getblock 000000000000000051d2e759c63a26e247f185ecb7926ed7a6624b↵

c31c2a717b true

{

"hash" : "000000000000000051d2e759c63a26e247f185ecb7926ed7a6624bc31c2a717↵

b",

"confirmations" : 2,

"size" : 248758,

"height" : 286384,

"version" : 2,

"merkleroot" : "9891747e37903016c3b77c7a0ef10acf467c530de52d84735bd555387↵

19f9916",

"tx" : [

"46e130ab3c67d31d2b2c7f8fbc1ca71604a72e6bc504c8a35f777286c6d89bf0",

"2d5625725b66d6c1da88b80b41e8c07dc5179ae2553361c96b14bcf1ce2c3868",

"923392fc41904894f32d7c127059bed27dbb3cfd550d87b9a2dc03824f249c80",

"f983739510a0f75837a82bfd9c96cd72090b15fa3928efb9cce95f6884203214",

"190e1b010d5a53161aa0733b953eb29ef1074070658aaa656f933ded1a177952",

"ee791ec8161440262f6e9144d5702f0057cef7e5767bc043879b7c2ff3ff5277",

"4c45449ff56582664abfadeb1907756d9bc90601d32387d9cfd4f1ef813b46be",

"3b031ed886c6d5220b3e3a28e3261727f3b4f0b29de5f93bc2de3e97938a8a53",

"14b533283751e34a8065952fd1cd2c954e3d37aaa69d4b183ac6483481e5497d",

"57b28365adaff61aaf60462e917a7cc9931904258127685c18f136eeaebd5d35",

"8c0cc19fff6b66980f90af39bee20294bc745baf32cd83199aa83a1f0cd6ca51",

"1b408640d54a1409d66ddaf3915a9dc2e8a6227439e8d91d2f74e704ba1cdae2",

"0568f4fad1fdeff4dc70b106b0f0ec7827642c05fe5d2295b9deba4f5c5f5168",

"9194bfe5756c7ec04743341a3605da285752685b9c7eebb594c6ed9ec9145f86",

"765038fc1d444c5d5db9163ba1cc74bba2b4f87dd87985342813bd24021b6faf",

"bff1caa9c20fa4eef33877765ee0a7d599fd1962417871ca63a2486476637136",

"d76aa89083f56fcce4d5bf7fcf20c0406abdac0375a2d3c62007f64aa80bed74",

"e57a4c70f91c8d9ba0ff0a55987ea578affb92daaa59c76820125f31a9584dfc",

"9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c14ae3",

#[... many more transactions ...]

],

"time" : 1392660808,

"nonce" : 3888130470,

"bits" : "19015f53",

"difficulty" : 3129573174.52228737,

"chainwork" : "000000000000000000000000000000000000000000001931d1658fc048↵

79e466",

"previousblockhash" : "0000000000000000177e61d5f6ba6b9450e0dade9f39c257b4↵

d48b4941ac77e7",

"nextblockhash" : "0000000000000001239d2c3bf7f4c68a4ca673e434702a57da8fe0↵

48 | Chapter 3: The Bitcoin Client

d829a92eb6"

The block contains 367 transactions and as you can see, the 18th transaction listed

(9ca8f9…) is the txid of the one crediting 50 millibits to our address. The height entry

tells us this is the 286384th block in the blockchain.

We can also retrieve a block by its block height using the getblockhash command,

which takes the block height as the parameter and returns the block hash for that block:

$ bitcoin-cli getblockhash 0000000000019d6689c085ae165831e934ff763ae46a2a6c17↵

2b3f1b60a8ce26f

Here, we retrieve the block hash of the “genesis block,” the first block mined by Satoshi

Nakamoto, at height zero. Retrieving this block shows:

$ bitcoin-cli getblock 000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1↵

b60a8ce26f

{

"hash" : "000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26↵

f",

"confirmations" : 286388,

"size" : 285,

"height" : 0,

"version" : 1,

"merkleroot" : "4a5e1e4baab89f3a32518a88c31bc87f618f76673e2cc77ab2127b7af↵

deda33b",

"tx" : [

"4a5e1e4baab89f3a32518a88c31bc87f618f76673e2cc77ab2127b7afdeda33b"

],

"time" : 1231006505,

"nonce" : 2083236893,

"bits" : "1d00ffff",

"difficulty" : 1.00000000,

"chainwork" : "0000000000000000000000000000000000000000000000000000000100↵

010001",

"nextblockhash" : "00000000839a8e6886ab5951d76f411475428afc90947ee320161b↵

bf18eb6048"

}

The getblock, getblockhash, and gettransaction commands can be used to explore

the blockchain database, programmatically.

Creating, Signing, and Submitting Transactions Based on

Unspent Outputs

Commands: listunspent, gettxout, createrawtransaction, decoderawtransac

tion, signrawtransaction, sendrawtransaction

Bitcoin’s transactions are based on the concept of spending “outputs,” which are the

result of previous transactions, to create a transaction chain that transfers ownership

Using Bitcoin Core’s JSON-RPC API from the Command Line | 49

from address to address. Our wallet has now received a transaction that assigned one

such output to our address. Once this is confirmed, we can spend that output.

First, we use the listunspent command to show all the unspent *confirmed* outputs in

our wallet:

$ bitcoin-cli listunspent

[

{

"txid" : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acbae2c↵

14ae3",

"vout" : 0,

"address" : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

"account" : "",

"scriptPubKey" : "76a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac",

"amount" : 0.05000000,

"confirmations" : 7

}

]

We see that the transaction 9ca8f9… created an output (with vout index 0) assigned to

the address 1hvzSo… for the amount of 50 millibits, which at this point has received

seven confirmations. Transactions use previously created outputs as their inputs by

referring to them by the previous txid and vout index. We will now create a transaction

that will spend the 0th vout of the txid 9ca8f9… as its input and assign it to a new output

that sends value to a new address.

First, let’s look at the specific output in more detail. We use gettxout to get the details

of this unspent output. Transaction outputs are always referenced by txid and vout, and

these are the parameters we pass to gettxout:

$ bitcoin-cli gettxout 9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309ac↵

bae2c14ae3 0

{

"bestblock" : "0000000000000001405ce69bd4ceebcdfdb537749cebe89d371eb37e13↵

899fd9",

"confirmations" : 7,

"value" : 0.05000000,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 07bdb518fa2e6089fd810235cf1100c9c13d1fd2

OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL"

]

},

"version" : 1,

50 | Chapter 3: The Bitcoin Client

"coinbase" : false

}

What we see here is the output that assigned 50 millibits to our address 1hvz…. To spend

this output we will create a new transaction. First, let’s make an address to which we

will send the money:

$ bitcoin-cli getnewaddress

1LnfTndy3qzXGN19Jwscj1T8LR3MVe3JDb

We will send 25 millibits to the new address 1LnfTn… we just created in our wallet. In

our new transaction, we will spend the 50 millibit output and send 25 millibits to this

new address. Because we have to spend the *whole* output from the previous transaction,

we must also generate some change. We will generate change back to the 1hvz… address,

sending the change back to the address from which the value originated. Finally, we will

also have to pay a fee for this transaction. To pay the fee, we will reduce the change

output by 0.5 millibits, and return 24.5 millibits in change. The difference between the

sum of the new outputs (25 mBTC + 24.5 mBTC = 49.5 mBTC) and the input (50 mBTC)

will be collected as a transaction fee by the miners.

We use createrawtransaction to create this transaction. As parameters to createraw

transaction we provide the transaction input (the 50 millibit unspent output from our

confirmed transaction) and the two transaction outputs (money sent to the new address

and change sent back to the previous address):

$ bitcoin-cli createrawtransaction '[{"txid" : "9ca8f969bd3ef5ec2a8685660fdbf↵

7a8bd365524c2e1fc66c309acbae2c14ae3", "vout" : 0}]' '{"1LnfTndy3qzXGN19Jwscj1↵

T8LR3MVe3JDb": 0.025, "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL": 0.0245}'

0100000001e34ac1e2baac09c366fce1c2245536bda8f7db0f6685862aecf53ebd69f9a89c000↵

0000000ffffffff02a0252600000000001976a914d90d36e98f62968d2bc9bbd68107564a156a↵

9bcf88ac50622500000000001976a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac0↵

0000000

The createrawtransaction command produces a raw hex string that encodes the

transaction details we supplied. Let’s confirm everything is correct by decoding this raw

string using the decoderawtransaction command:

$ bitcoin-cli decoderawtransaction 0100000001e34ac1e2baac09c366fce1c2245536bd↵

a8f7db0f6685862aecf53ebd69f9a89c0000000000ffffffff02a0252600000000001976a914d↵

90d36e98f62968d2bc9bbd68107564a156a9bcf88ac50622500000000001976a91407bdb518fa↵

2e6089fd810235cf1100c9c13d1fd288ac00000000

{

"txid" : "0793299cb26246a8d24e468ec285a9520a1c30fcb5b6125a102e3fc05d4f3cb↵

a",

"version" : 1,

"locktime" : 0,

"vin" : [

{

"txid" : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acb↵

Using Bitcoin Core’s JSON-RPC API from the Command Line | 51

ae2c14ae3",

"vout" : 0,

"scriptSig" : {

"asm" : "",

"hex" : ""

},

"sequence" : 4294967295

}

],

"vout" : [

{

"value" : 0.02500000,

"n" : 0,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 d90d36e98f62968d2bc9bbd68107564a15↵

6a9bcf OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a914d90d36e98f62968d2bc9bbd68107564a156a9bcf88ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1LnfTndy3qzXGN19Jwscj1T8LR3MVe3JDb"

]

}

},

{

"value" : 0.02450000,

"n" : 1,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 07bdb518fa2e6089fd810235cf1100c9c1↵

3d1fd2 OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL"

]

}

}

]

}

That looks correct! Our new transaction “consumes” the unspent output from our confirmed

transaction and then spends it in two outputs, one for 25 millibits to our new

address and one for 24.5 millibits as change back to the original address. The difference

of 0.5 millibits represents the transaction fee and will be credited to the miner who finds

the block that includes our transaction.

As you might notice, the transaction contains an empty scriptSig because we haven’t

signed it yet. Without a signature, this transaction is meaningless; we haven’t yet proven

that we *own* the address from which the unspent output is sourced. By signing, we

remove the encumbrance on the output and prove that we own this output and can

52 | Chapter 3: The Bitcoin Client

spend it. We use the signrawtransaction command to sign the transaction. It takes

the raw transaction hex string as the parameter:

An encrypted wallet must be unlocked before a transaction is signed

because signing requires access to the secret keys in the wallet.

$ bitcoin-cli walletpassphrase foo 360

$ bitcoin-cli signrawtransaction 0100000001e34ac1e2baac09c366fce1c2245536bda8↵

f7db0f6685862aecf53ebd69f9a89c0000000000ffffffff02a0252600000000001976a914d90↵

d36e98f62968d2bc9bbd68107564a156a9bcf88ac50622500000000001976a91407bdb518fa2e↵

6089fd810235cf1100c9c13d1fd288ac00000000

{

"hex" : "0100000001e34ac1e2baac09c366fce1c2245536bda8f7db0f6685862aecf53e↵

bd69f9a89c000000006a47304402203e8a16522da80cef66bacfbc0c800c6d52c4a26d1d86a54↵

e0a1b76d661f020c9022010397f00149f2a8fb2bc5bca52f2d7a7f87e3897a273ef54b277e4af↵

52051a06012103c9700559f690c4a9182faa8bed88ad8a0c563777ac1d3f00fd44ea6c71dc512↵

7ffffffff02a0252600000000001976a914d90d36e98f62968d2bc9bbd68107564a156a9bcf88↵

ac50622500000000001976a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac00000000",

"complete" : true

}

The signrawtransaction command returns another hex-encoded raw transaction. We

decode it to see what changed, with decoderawtransaction:

$ bitcoin-cli decoderawtransaction0100000001e34ac1e2baac09c366fce1c2245536bda↵

8f7db0f6685862aecf53ebd69f9a89c000000006a47304402203e8a16522da80cef66bacfbc0c↵

800c6d52c4a26d1d86a54e0a1b76d661f020c9022010397f00149f2a8fb2bc5bca52f2d7a7f87↵

e3897a273ef54b277e4af52051a06012103c9700559f690c4a9182faa8bed88ad8a0c563777ac↵

1d3f00fd44ea6c71dc5127ffffffff02a0252600000000001976a914d90d36e98f62968d2bc9b↵

bd68107564a156a9bcf88ac50622500000000001976a91407bdb518fa2e6089fd810235cf1100↵

c9c13d1fd288ac00000000

{

"txid" : "ae74538baa914f3799081ba78429d5d84f36a0127438e9f721dff584ac17b34↵

6",

"version" : 1,

"locktime" : 0,

"vin" : [

{

"txid" : "9ca8f969bd3ef5ec2a8685660fdbf7a8bd365524c2e1fc66c309acb↵

ae2c14ae3",

"vout" : 0,

"scriptSig" : {

"asm" : "304402203e8a16522da80cef66bacfbc0c800c6d52c4a26d1d86↵

a54e0a1b76d661f020c9022010397f00149f2a8fb2bc5bca52f2d7a7f87e3897a273ef54b277e↵

4af52051a0601 03c9700559f690c4a9182faa8bed88ad8a0c563777ac1d3f00fd44ea6c71dc5↵

127",

Using Bitcoin Core’s JSON-RPC API from the Command Line | 53

"hex" : "47304402203e8a16522da80cef66bacfbc0c800c6d52c4a26d1d↵

86a54e0a1b76d661f020c9022010397f00149f2a8fb2bc5bca52f2d7a7f87e3897a273ef54b27↵

7e4af52051a06012103c9700559f690c4a9182faa8bed88ad8a0c563777ac1d3f00fd44ea6c71↵

dc5127"

},

"sequence" : 4294967295

}

],

"vout" : [

{

"value" : 0.02500000,

"n" : 0,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 d90d36e98f62968d2bc9bbd68107564a15↵

6a9bcf OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a914d90d36e98f62968d2bc9bbd68107564a156a9bcf88ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1LnfTndy3qzXGN19Jwscj1T8LR3MVe3JDb"

]

}

},

{

"value" : 0.02450000,

"n" : 1,

"scriptPubKey" : {

"asm" : "OP\_DUP OP\_HASH160 07bdb518fa2e6089fd810235cf1100c9c1↵

3d1fd2 OP\_EQUALVERIFY OP\_CHECKSIG",

"hex" : "76a91407bdb518fa2e6089fd810235cf1100c9c13d1fd288ac",

"reqSigs" : 1,

"type" : "pubkeyhash",

"addresses" : [

"1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL"

]

}

}

]

}

Now, the inputs used in the transaction contain a scriptSig, which is a digital signature

proving ownership of address 1hvz… and removing the encumbrance on the output so

that it can be spent. The signature makes this transaction verifiable by any node in the

bitcoin network.

Now it’s time to submit the newly created transaction to the network. We do that with

the command sendrawtransaction, which takes the raw hex string produced by sign

rawtransaction. This is the same string we just decoded:

$ bitcoin-cli sendrawtransaction0100000001e34ac1e2baac09c366fce1c2245536bda8f↵

7db0f6685862aecf53ebd69f9a89c000000006a47304402203e8a16522da80cef66bacfbc0c80↵

0c6d52c4a26d1d86a54e0a1b76d661f020c9022010397f00149f2a8fb2bc5bca52f2d7a7f87e3↵

54 | Chapter 3: The Bitcoin Client

897a273ef54b277e4af52051a06012103c9700559f690c4a9182faa8bed88ad8a0c563777ac1d↵

3f00fd44ea6c71dc5127ffffffff02a0252600000000001976a914d90d36e98f62968d2bc9bbd↵

68107564a156a9bcf88ac50622500000000001976a91407bdb518fa2e6089fd810235cf1100c9↵

c13d1fd288ac00000000ae74538baa914f3799081ba78429d5d84f36a0127438e9f721dff584a↵

c17b346

The command sendrawtransaction returns a *transaction hash (txid)* as it submits the

transaction on the network. We can now query that transaction ID with gettransac

tion:

$ bitcoin-cli gettransaction ae74538baa914f3799081ba78429d5d84f36a0127438e9f7↵

21dff584ac17b346

{

**"amount"** : 0.00000000,

**"fee"** : -0.00050000,

**"confirmations"** : 0,

**"txid"** : "ae74538baa914f3799081ba78429d5d84f36a0127438e9f721dff584ac17b346",

**"time"** : 1392666702,

**"timereceived"** : 1392666702,

**"details"** : [

{

**"account"** : "",

**"address"** : "1LnfTndy3qzXGN19Jwscj1T8LR3MVe3JDb",

**"category"** : "send",

**"amount"** : -0.02500000,

**"fee"** : -0.00050000

},

{

**"account"** : "",

**"address"** : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

**"category"** : "send",

**"amount"** : -0.02450000,

**"fee"** : -0.00050000

},

{

**"account"** : "",

**"address"** : "1LnfTndy3qzXGN19Jwscj1T8LR3MVe3JDb",

**"category"** : "receive",

**"amount"** : 0.02500000

},

{

**"account"** : "",

**"address"** : "1hvzSofGwT8cjb8JU7nBsCSfEVQX5u9CL",

**"category"** : "receive",

**"amount"** : 0.02450000

}

]

}

Using Bitcoin Core’s JSON-RPC API from the Command Line | 55

As before, we can also examine this in more detail using the getrawtransaction and

decodetransaction commands. These commands will return the exact same hex string

that we produced and decoded previously just before we sent it on the network.

Alternative Clients, Libraries, and Toolkits

Beyond the reference client (bitcoind), other clients and libraries can be used to interact

with the bitcoin network and data structures. These are implemented in a variety of

programming languages, offering programmers native interfaces in their own language.

Alternative implementations include:

*libbitcoin and sx tools*

A C++ multithreaded full-node client and library with command-line tools

*bitcoinj*

A Java full-node client library

*btcd*

A Go language full-node bitcoin client

*Bits of Proof (BOP)*

A Java enterprise-class implementation of bitcoin

*picocoin*

A C implementation of a lightweight client library for bitcoin

*pybitcointools*

A Python bitcoin library

*pycoin*

Another Python bitcoin library

Many more libraries exist in a variety of other programming languages and more are

created all the time.

Libbitcoin and sx Tools

The libbitcoin library is a C++ scalable multithreaded and modular implementation

that supports a full-node client and a command-line toolset called sx, which offers many

of the same capabilities as the bitcoind client commands we illustrated in this chapter.

The sx tools also offer some key management and manipulation tools that are not offered

by bitcoind, including type-2 deterministic keys and key mnemonics.

Installing sx

To install sx and the supporting library libbitcoin, download and run the online installer

on a Linux system:

56 | Chapter 3: The Bitcoin Client

$ wget http://sx.dyne.org/install-sx.sh

$ sudo bash ./install-sx.sh

You should now have the sx tools installed. Type sx with no parameters to display the

help text, which lists all the available commands (see Appendix D).

The sx toolkit offers many useful commands for encoding and decoding

addresses, and converting to and from different formats and

representations. Use them to explore the various formats such as

Base58, Base58Check, hex, etc.

pycoin

The Python library *pycoin*, originally written and maintained by Richard Kiss, is a

Python-based library that supports manipulation of bitcoin keys and transactions, even

supporting the scripting language enough to properly deal with nonstandard transactions.

The pycoin library supports both Python 2 (2.7.x) and Python 3 (after 3.3), and comes

with some handy command-line utilities, ku and tx. To install pycoin 0.42 under Python

3 in a virtual environment (venv), use the following:

$ python3 -m venv /tmp/pycoin

$ . /tmp/pycoin/bin/activate

$ pip install pycoin==0.42

Downloading/unpacking pycoin==0.42

Downloading pycoin-0.42.tar.gz (66kB): 66kB downloaded

Running setup.py (path:/tmp/pycoin/build/pycoin/setup.py) egg\_info for package

pycoin

Installing collected packages: pycoin

Running setup.py install for pycoin

Installing tx script to /tmp/pycoin/bin

Installing cache\_tx script to /tmp/pycoin/bin

Installing bu script to /tmp/pycoin/bin

Installing fetch\_unspent script to /tmp/pycoin/bin

Installing block script to /tmp/pycoin/bin

Installing spend script to /tmp/pycoin/bin

Installing ku script to /tmp/pycoin/bin

Installing genwallet script to /tmp/pycoin/bin

Successfully installed pycoin

Cleaning up...

$

Here’s a sample Python script to fetch and spend some bitcoin using the pycoin library:

*#!/usr/bin/env python*

**from pycoin.key import** Key

Alternative Clients, Libraries, and Toolkits | 57

**from pycoin.key.validate import** is\_address\_valid, is\_wif\_valid

**from pycoin.services import** spendables\_for\_address

**from pycoin.tx.tx\_utils import** create\_signed\_tx

**def** get\_address(which):

**while** 1:

**print**("enter the %s address=> " % which, end='')

address = input()

is\_valid = is\_address\_valid(address)

**if** is\_valid:

**return** address

**print**("invalid address, please try again")

src\_address = get\_address("source")

spendables = spendables\_for\_address(src\_address)

**print**(spendables)

**while** 1:

**print**("enter the WIF for %s=> " % src\_address, end='')

wif = input()

is\_valid = is\_wif\_valid(wif)

**if** is\_valid:

**break**

**print**("invalid wif, please try again")

key = Key.from\_text(wif)

**if** src\_address **not in** (key.address(use\_uncompressed=False), key.address(use\_un

compressed=True)):

**print**("\*\* WIF doesn't correspond to %s" % src\_address)

**print**("The secret exponent is %d" % key.secret\_exponent())

dst\_address = get\_address("destination")

tx = create\_signed\_tx(spendables, payables=[dst\_address], wifs=[wif])

**print**("here is the signed output transaction")

**print**(tx.as\_hex())

For examples using the command-line utilities ku and tx, see Appendix B.

btcd

btcd is a full-node bitcoin implementation written in Go. It currently downloads, validates,

and serves the blockchain using the exact rules (including bugs) for block acceptance

as the reference implementation, bitcoind. It also properly relays newly mined

blocks, maintains a transaction pool, and relays individual transactions that have not

yet made it into a block. It ensures that all individual transactions admitted to the pool

follow the rules required and also includes the vast majority of the more strict checks

that filter transactions based on miner requirements (“standard” transactions).

58 | Chapter 3: The Bitcoin Client

One key difference between btcd and bitcoind is that btcd does not include wallet functionality,

and this was a very intentional design decision. This means you can’t actually

make or receive payments directly with btcd. That functionality is provided by the

btcwallet and btcgui projects, which are both under active development. Other notable

differences between btcd and bitcoind include btcd support for both HTTP POST requests

(such as bitcoind) and the preferred Websockets, and the fact that btcd’s RPC

connections are TLS-enabled by default.

Installing btcd

To install btcd for Windows, download and run the msi available at GitHub, or run the

following command on Linux, assuming you already have installed the Go language:

$ go get github.com/conformal/btcd/...

To update btcd to the latest version, just run:

$ go get -u -v github.com/conformal/btcd/...

Controlling btcd

btcd has a number of configuration options, which you can view by running:

$ btcd --help

btcd comes prepackaged with some goodies such as btcctl, which is a command-line

utility that can be used to both control and query btcd via RPC. btcd does not enable

its RPC server by default; you must configure at minimum both an RPC username and

password in the following configuration files:

• *btcd.conf*:

**[Application Options]**

rpcuser=myuser

rpcpass=SomeDecentp4ssw0rd

• *btcctl.conf*:

**[Application Options]**

rpcuser=myuser

rpcpass=SomeDecentp4ssw0rd

Or if you want to override the configuration files from the command line:

$ btcd -u myuser -P SomeDecentp4ssw0rd

$ btcctl -u myuser -P SomeDecentp4ssw0rd

For a list of available options, run the following:

$ btcctl --help

Alternative Clients, Libraries, and Toolkits | 59

CHAPTER 4

Keys, Addresses, Wallets

Introduction

Ownership of bitcoin is established through *digital keys*, *bitcoin addresses*, and *digital*

*signatures*. The digital keys are not actually stored in the network, but are instead created

and stored by users in a file, or simple database, called a *wallet*. The digital keys in a

user’s wallet are completely independent of the bitcoin protocol and can be generated

and managed by the user’s wallet software without reference to the blockchain or access

to the Internet. Keys enable many of the interesting properties of bitcoin, including decentralized

trust and control, ownership attestation, and the cryptographic-proof security

model.

Every bitcoin transaction requires a valid signature to be included in the blockchain,

which can only be generated with valid digital keys; therefore, anyone with a copy of

those keys has control of the bitcoin in that account. Keys come in pairs consisting of a

private (secret) key and a public key. Think of the public key as similar to a bank account

number and the private key as similar to the secret PIN, or signature on a check that

provides control over the account. These digital keys are very rarely seen by the users

of bitcoin. For the most part, they are stored inside the wallet file and managed by the

bitcoin wallet software.

In the payment portion of a bitcoin transaction, the recipient’s public key is represented

by its digital fingerprint, called a *bitcoin address*, which is used in the same way as the

beneficiary name on a check (i.e., “Pay to the order of ”). In most cases, a bitcoin address

is generated from and corresponds to a public key. However, not all bitcoin addresses

represent public keys; they can also represent other beneficiaries such as scripts, as we

will see later in this chapter. This way, bitcoin addresses abstract the recipient of funds,

making transaction destinations flexible, similar to paper checks: a single payment instrument

that can be used to pay into people’s accounts, pay into company accounts,

61

pay for bills, or pay to cash. The bitcoin address is the only representation of the keys

that users will routinely see, because this is the part they need to share with the world.

In this chapter we will introduce wallets, which contain cryptographic keys. We will

look at how keys are generated, stored, and managed. We will review the various encoding

formats used to represent private and public keys, addresses, and script addresses.

Finally, we will look at special uses of keys: to sign messages, to prove ownership,

and to create vanity addresses and paper wallets.

Public Key Cryptography and Cryptocurrency

Public key cryptography was invented in the 1970s and is a mathematical foundation

for computer and information security.

Since the invention of public key cryptography, several suitable mathematical functions,

such as prime number exponentiation and elliptic curve multiplication, have been discovered.

These mathematical functions are practically irreversible, meaning that they

are easy to calculate in one direction and infeasible to calculate in the opposite direction.

Based on these mathematical functions, cryptography enables the creation of digital

secrets and unforgeable digital signatures. Bitcoin uses elliptic curve multiplication as

the basis for its public key cryptography.

In bitcoin, we use public key cryptography to create a key pair that controls access to

bitcoins. The key pair consists of a private key and—derived from it—a unique public

key. The public key is used to receive bitcoins, and the private key is used to sign transactions

to spend those bitcoins.

There is a mathematical relationship between the public and the private key that allows

the private key to be used to generate signatures on messages. This signature can be

validated against the public key without revealing the private key.

When spending bitcoins, the current bitcoin owner presents her public key and a signature

(different each time, but created from the same private key) in a transaction to

spend those bitcoins. Through the presentation of the public key and signature, everyone

in the bitcoin network can verify and accept the transaction as valid, confirming

that the person transferring the bitcoins owned them at the time of the transfer.

In most wallet implementations, the private and public keys are stored

together as a *key pair* for convenience. However, the public key can

be calculated from the private key, so storing only the private key is

also possible.

62 | Chapter 4: Keys, Addresses, Wallets

Private and Public Keys

A bitcoin wallet contains a collection of key pairs, each consisting of a private key and

a public key. The private key (k) is a number, usually picked at random. From the private

key, we use elliptic curve multiplication, a one-way cryptographic function, to generate

a public key (K). From the public key (K), we use a one-way cryptographic hash function

to generate a bitcoin address (A). In this section, we will start with generating the private

key, look at the elliptic curve math that is used to turn that into a public key, and finally,

generate a bitcoin address from the public key. The relationship between private key,

public key, and bitcoin address is shown in Figure 4-1.

*Figure 4-1. Private key, public key, and bitcoin address*

Private Keys

A private key is simply a number, picked at random. Ownership and control over the

private key is the root of user control over all funds associated with the corresponding

bitcoin address. The private key is used to create signatures that are required to spend

bitcoins by proving ownership of funds used in a transaction. The private key must

remain secret at all times, because revealing it to third parties is equivalent to giving

them control over the bitcoins secured by that key. The private key must also be backed

up and protected from accidental loss, because if it’s lost it cannot be recovered and the

funds secured by it are forever lost, too.

The bitcoin private key is just a number. You can pick your private

keys randomly using just a coin, pencil, and paper: toss a coin 256

times and you have the binary digits of a random private key you can

use in a bitcoin wallet. The public key can then be generated from the

private key.

Generating a private key from a random number

The first and most important step in generating keys is to find a secure source of entropy,

or randomness. Creating a bitcoin key is essentially the same as “Pick a number between

1 and 2256.” The exact method you use to pick that number does not matter as long as it

is not predictable or repeatable. Bitcoin software uses the underlying operating system’s

Introduction | 63

random number generators to produce 256 bits of entropy (randomness). Usually, the

OS random number generator is initialized by a human source of randomness, which

is why you may be asked to wiggle your mouse around for a few seconds. For the truly

paranoid, nothing beats dice, pencil, and paper.

More accurately, the private key can be any number between 1 and n - 1, where n is a

constant (n = 1.158 \* 1077, slightly less than 2256) defined as the order of the elliptic curve

used in bitcoin (see “Elliptic Curve Cryptography Explained” on page 65). To create such

a key, we randomly pick a 256-bit number and check that it is less than n - 1. In

programming terms, this is usually achieved by feeding a larger string of random bits,

collected from a cryptographically secure source of randomness, into the SHA256 hash

algorithm that will conveniently produce a 256-bit number. If the result is less than n -

1, we have a suitable private key. Otherwise, we simply try again with another random

number.

Do not write your own code to create a random number or use a

“simple” random number generator offered by your programming

language. Use a cryptographically secure pseudo-random number

generator (CSPRNG) with a seed from a source of sufficient entropy.

Study the documentation of the random number generator library

you choose to make sure it is cryptographically secure. Correct

implementation of the CSPRNG is critical to the security of the

keys.

The following is a randomly generated private key (k) shown in hexadecimal format

(256 binary digits shown as 64 hexadecimal digits, each 4 bits):

1E99423A4ED27608A15A2616A2B0E9E52CED330AC530EDCC32C8FFC6A526AEDD

The size of bitcoin’s private key space, 2256 is an unfathomably large

number. It is approximately 1077 in decimal. The visible universe is

estimated to contain 1080 atoms.

To generate a new key with the Bitcoin Core client (see Chapter 3), use the getnewad

dress command. For security reasons it displays the public key only, not the private

key. To ask bitcoind to expose the private key, use the dumpprivkey command. The

dumpprivkey command shows the private key in a Base58 checksum-encoded format

called the *Wallet Import Format* (WIF), which we will examine in more detail in “Private

key formats” on page 76. Here’s an example of generating and displaying a private key

using these two commands:

64 | Chapter 4: Keys, Addresses, Wallets

$ bitcoind getnewaddress

1J7mdg5rbQyUHENYdx39WVWK7fsLpEoXZy

$ bitcoind dumpprivkey 1J7mdg5rbQyUHENYdx39WVWK7fsLpEoXZy

KxFC1jmwwCoACiCAWZ3eXa96mBM6tb3TYzGmf6YwgdGWZgawvrtJ

The dumpprivkey command opens the wallet and extracts the private key that was generated

by the getnewaddress command. It is not otherwise possible for bitcoind to know

the private key from the public key, unless they are both stored in the wallet.

The dumpprivkey command is not generating a private key from a

public key, as this is impossible. The command simply reveals the

private key that is already known to the wallet and which was generated

by the getnewaddress command.

You can also use the command-line sx tools (see “Libbitcoin and sx Tools” on page 56)

to generate and display private keys with the sx command newkey:

$ sx newkey

5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

Public Keys

The public key is calculated from the private key using elliptic curve multiplication,

which is irreversible: *K* = *k* \**G* where *k* is the private key, *G* is a constant point called

the *generator point* and *K* is the resulting public key. The reverse operation, known as

“finding the discrete logarithm”—calculating *k* if you know *K*—is as difficult as trying

all possible values of k, i.e., a brute-force search. Before we demonstrate how to generate

a public key from a private key, let’s look at elliptic curve cryptography in a bit more

detail.

Elliptic Curve Cryptography Explained

Elliptic curve cryptography is a type of asymmetric or public-key cryptography based

on the discrete logarithm problem as expressed by addition and multiplication on the

points of an elliptic curve.

Figure 4-2 is an example of an elliptic curve, similar to that used by bitcoin.

Introduction | 65

*Figure 4-2. An elliptic curve*

Bitcoin uses a specific elliptic curve and set of mathematical constants, as defined in a

standard called secp256k1, established by the National Institute of Standards and Technology

(NIST). The secp256k1 curve is defined by the following function, which produces

an elliptic curve:

*y* 2 = (*x* 3 + 7) over ( *p*)

or

*y* 2 mod *p* = (*x* 3 + 7) mod *p*

The *mod p* (modulo prime number p) indicates that this curve is over a finite field of

prime order *p*, also written as *p*, where p = 2256 – 232 – 29 – 28 – 27 – 26 – 24 – 1, a very

large prime number.

Because this curve is defined over a finite field of prime order instead of over the real

numbers, it looks like a pattern of dots scattered in two dimensions, which makes it

difficult to visualize. However, the math is identical as that of an elliptic curve over the

real numbers. As an example, Figure 4-3 shows the same elliptic curve over a much

smaller finite field of prime order 17, showing a pattern of dots on a grid. The secp256k1

bitcoin elliptic curve can be thought of as a much more complex pattern of dots on a

unfathomably large grid.

66 | Chapter 4: Keys, Addresses, Wallets

*Figure 4-3. Elliptic curve cryptography: visualizing an elliptic curve over F(p), with*

*p=17*

So, for example, the following is a point P with coordinates (x,y) that is a point on the

secp256k1 curve. You can check this yourself using Python:

P =

(55066263022277343669578718895168534326250603453777594175500187360389116729240,

32670510020758816978083085130507043184471273380659243275938904335757337482424)

Python 3.4.0 (default, Mar 30 2014, 19:23:13)

[GCC 4.2.1 Compatible Apple LLVM 5.1 (clang-503.0.38)] on darwin

Type "help", "copyright", "credits" or "license" for more information.

**>>>** p =

115792089237316195423570985008687907853269984665640564039457584007908834671663

**>>>** x =

55066263022277343669578718895168534326250603453777594175500187360389116729240

**>>>** y =

32670510020758816978083085130507043184471273380659243275938904335757337482424

**>>>** (x \*\* 3 + 7 - y\*\*2) % p

0

In elliptic curve math, there is a point called the “point at infinity,” which roughly corresponds

to the role of 0 in addition. On computers, it’s sometimes represented by x =

Introduction | 67

y = 0 (which doesn’t satisfy the elliptic curve equation, but it’s an easy separate case that

can be checked).

There is also a + operator, called “addition,” which has some properties similar to the

traditional addition of real numbers that grade school children learn. Given two points

P1 and P2 on the elliptic curve, there is a third point P3 = P1 + P2, also on the elliptic

curve.

Geometrically, this third point P3 is calculated by drawing a line between P1 and P2. This

line will intersect the elliptic curve in exactly one additional place. Call this point P3' =

(x, y). Then reflect in the x-axis to get P3 = (x, –y).

There are a couple of special cases that explain the need for the “point at infinity.”

If P1 and P2 are the same point, the line “between” P1 and P2 should extend to be the

tangent on the curve at this point P1. This tangent will intersect the curve in exactly one

new point. You can use techniques from calculus to determine the slope of the tangent

line. These techniques curiously work, even though we are restricting our interest to

points on the curve with two integer coordinates!

In some cases (i.e., if P1 and P2 have the same x values but different y values), the tangent

line will be exactly vertical, in which case P3 = “point at infinity.”

If P1 is the “point at infinity,” then the sum P1 + P2 = P2. Similary, if P2 is the point at

infinity, then P1 + P2 = P1. This shows how the point at infinity plays the role of 0.

It turns out that + is associative, which means that (A+B)C = A(B+C). That means we

can write A+B+C without parentheses without any ambiguity.

Now that we have defined addition, we can define multiplication in the standard way

that extends addition. For a point P on the elliptic curve, if k is a whole number, then

kP = P + P + P + … + P (k times). Note that k is sometimes confusingly called an

“exponent” in this case.

Generating a Public Key

Starting with a private key in the form of a randomly generated number *k*, we multiply

it by a predetermined point on the curve called the *generator point G* to produce another

point somewhere else on the curve, which is the corresponding public key *K*. The generator

point is specified as part of the secp256k1 standard and is always the same for all

keys in bitcoin:

*K* = *k* \**G*

where k is the private key, G is the generator point, and K is the resulting public key, a

point on the curve. Because the generator point is always the same for all bitcoin users,

68 | Chapter 4: Keys, Addresses, Wallets

a private key k multiplied with G will always result in the same public key K. The relationship

between k and K is fixed, but can only be calculated in one direction, from k

to K. That’s why a bitcoin address (derived from K) can be shared with anyone and does

not reveal the user’s private key (k).

A private key can be converted into a public key, but a public key

cannot be converted back into a private key because the math only

works one way.

Implementing the elliptic curve multiplication, we take the private key k generated

previously and multiply it with the generator point G to find the public key K:

K = 1E99423A4ED27608A15A2616A2B0E9E52CED330AC530EDCC32C8FFC6A526AEDD \* G

Public Key K is defined as a point K = (x,y):

K = (x, y)

where,

x = F028892BAD7ED57D2FB57BF33081D5CFCF6F9ED3D3D7F159C2E2FFF579DC341A

y = 07CF33DA18BD734C600B96A72BBC4749D5141C90EC8AC328AE52DDFE2E505BDB

To visualize multiplication of a point with an integer, we will use the simpler elliptic

curve over the real numbers—remember, the math is the same. Our goal is to find the

multiple kG of the generator point G. That is the same as adding G to itself, k times in

a row. In elliptic curves, adding a point to itself is the equivalent of drawing a tangent

line on the point and finding where it intersects the curve again, then reflecting that

point on the x-axis.

Figure 4-4 shows the process for deriving G, 2G, 4G, as a geometric operation on the

curve.

Most bitcoin implementations use the OpenSSL cryptographic library

to do the elliptic curve math. For example, to derive the public

key, the function EC\_POINT\_mul() is used.

Introduction | 69

*Figure 4-4. Elliptic curve cryptography: Visualizing the multiplication of a point G by*

*an integer k on an elliptic curve*

Bitcoin Addresses

A bitcoin address is a string of digits and characters that can be shared with anyone who

wants to send you money. Addresses produced from public keys consist of a string of

numbers and letters, beginning with the digit “1”. Here’s an example of a bitcoin address:

1J7mdg5rbQyUHENYdx39WVWK7fsLpEoXZy

The bitcoin address is what appears most commonly in a transaction as the “recipient”

of the funds. If we were to compare a bitcoin transaction to a paper check, the bitcoin

address is the beneficiary, which is what we write on the line after “Pay to the order of.”

On a paper check, that beneficiary can sometimes be the name of a bank account holder,

but can also include corporations, institutions, or even cash. Because paper checks do

not need to specify an account, but rather use an abstract name as the recipient of funds,

that makes paper checks very flexible as payment instruments. Bitcoin transactions use

a similar abstraction, the bitcoin address, to make them very flexible. A bitcoin address

can represent the owner of a private/public key pair, or it can represent something else,

such as a payment script, as we will see in “Pay-to-Script-Hash (P2SH)” on page 132. For

now, let’s examine the simple case, a bitcoin address that represents, and is derived from,

a public key.

70 | Chapter 4: Keys, Addresses, Wallets

The bitcoin address is derived from the public key through the use of one-way cryptographic

hashing. A “hashing algorithm” or simply “hash algorithm” is a one-way function

that produces a fingerprint or “hash” of an arbitrary-sized input. Cryptographic

hash functions are used extensively in bitcoin: in bitcoin addresses, in script addresses,

and in the mining proof-of-work algorithm. The algorithms used to make a bitcoin

address from a public key are the Secure Hash Algorithm (SHA) and the RACE Integrity

Primitives Evaluation Message Digest (RIPEMD), specifically SHA256 and RIPEMD160.

Starting with the public key K, we compute the SHA256 hash and then compute the

RIPEMD160 hash of the result, producing a 160-bit (20-byte) number:

*A* = *RIPEMD*160(*SHA*256(*K*))

where K is the public key and A is the resulting bitcoin address.

A bitcoin address is *not* the same as a public key. Bitcoin addresses

are derived from a public key using a one-way function.

Bitcoin addresses are almost always presented to users in an encoding called

“Base58Check” (see “Base58 and Base58Check Encoding” on page 72), which uses 58

characters (a Base58 number system) and a checksum to help human readability, avoid

ambiguity, and protect against errors in address transcription and entry. Base58Check

is also used in many other ways in bitcoin, whenever there is a need for a user to read

and correctly transcribe a number, such as a bitcoin address, a private key, an encrypted

key, or a script hash. In the next section we will examine the mechanics of Base58Check

encoding and decoding, and the resulting representations. Figure 4-5 illustrates the

conversion of a public key into a bitcoin address.

Bitcoin Addresses | 71

*Figure 4-5. Public key to bitcoin address: conversion of a public key into a bitcoin address*

Base58 and Base58Check Encoding

In order to represent long numbers in a compact way, using fewer symbols, many computer

systems use mixed-alphanumeric representations with a base (or radix) higher

than 10. For example, whereas the traditional decimal system uses the 10 numerals 0

through 9, the hexadecimal system uses 16, with the letters A through F as the six

additional symbols. A number represented in hexadecimal format is shorter than the

equivalent decimal representation. Even more compact, Base-64 representation uses 26

lower-case letters, 26 capital letters, 10 numerals, and two more characters such as “+”

and “/” to transmit binary data over text-based media such as email. Base-64 is most

commonly used to add binary attachments to email. Base58 is a text-based binary-

72 | Chapter 4: Keys, Addresses, Wallets

encoding format developed for use in bitcoin and used in many other cryptocurrencies.

It offers a balance between compact representation, readability, and error detection and

prevention. Base58 is a subset of Base64, using the upper- and lowercase letters and

numbers, but omitting some characters that are frequently mistaken for one another

and can appear identical when displayed in certain fonts. Specifically, Base58 is Base64

without the 0 (number zero), O (capital o), l (lower L), I (capital i), and the symbols “\

+” and “/”. Or, more simply, it is a set of lower and capital letters and numbers without

the four (0, O, l, I) just mentioned.

*Example 4-1. bitcoin’s Base58 alphabet*

123456789ABCDEFGHJKLMNPQRSTUVWXYZabcdefghijkmnopqrstuvwxyz

To add extra security against typos or transcription errors, Base58Check is a Base58

encoding format, frequently used in bitcoin, which has a built-in error-checking code.

The checksum is an additional four bytes added to the end of the data that is being

encoded. The checksum is derived from the hash of the encoded data and can therefore

be used to detect and prevent transcription and typing errors. When presented with a

Base58Check code, the decoding software will calculate the checksum of the data and

compare it to the checksum included in the code. If the two do not match, that indicates

that an error has been introduced and the Base58Check data is invalid. For example,

this prevents a mistyped bitcoin address from being accepted by the wallet software as

a valid destination, an error that would otherwise result in loss of funds.

To convert data (a number) into a Base58Check format, we first add a prefix to the data,

called the “version byte,” which serves to easily identify the type of data that is encoded.

For example, in the case of a bitcoin address the prefix is zero (0x00 in hex), whereas

the prefix used when encoding a private key is 128 (0x80 in hex). A list of common

version prefixes is shown in Table 4-1.

Next, we compute the “double-SHA” checksum, meaning we apply the SHA256 hashalgorithm

twice on the previous result (prefix and data):

checksum = SHA256(SHA256(prefix+data))

From the resulting 32-byte hash (hash-of-a-hash), we take only the first four bytes.

These four bytes serve as the error-checking code, or checksum. The checksum is concatenated

(appended) to the end.

The result is composed of three items: a prefix, the data, and a checksum. This result is

encoded using the Base58 alphabet described previously. Figure 4-6 illustrates the

Base58Check encoding process.

Bitcoin Addresses | 73

*Figure 4-6. Base58Check encoding: a Base58, versioned, and checksummed format for*

*unambiguously encoding bitcoin data*

In bitcoin, most of the data presented to the user is Base58Check-encoded to make it

compact, easy to read, and easy to detect errors. The version prefix in Base58Check

encoding is used to create easily distinguishable formats, which when encoded in Base58

contain specific characters at the beginning of the Base58Check-encoded payload. These

characters make it easy for humans to identify the type of data that is encoded and how

to use it. This is what differentiates, for example, a Base58Check-encoded bitcoin address

that starts with a 1 from a Base58Check-encoded private key WIF format that

starts with a 5. Some example version prefixes and the resulting Base58 characters are

shown in Table 4-1.

*Table 4-1. Base58Check version prefix and encoded result examples*

Type Version prefix (hex) Base58 result prefix

Bitcoin Address 0x00 1

Pay-to-Script-Hash Address 0x05 3

Bitcoin Testnet Address 0x6F m or n

74 | Chapter 4: Keys, Addresses, Wallets

Type Version prefix (hex) Base58 result prefix

Private Key WIF 0x80 5, K or L

BIP38 Encrypted Private Key 0x0142 6P

BIP32 Extended Public Key 0x0488B21E xpub

Let’s look at the complete process of creating a bitcoin address, from a private key, to a

public key (a point on the elliptic curve), to a double-hashed address and finally, the

Base58Check encoding. The C++ code in Example 4-2 shows the complete step-by-step

process, from private key to Base58Check-encoded bitcoin address. The code example

uses the libbitcoin library introduced in “Alternative Clients, Libraries, and Toolkits”

on page 56 for some helper functions.

*Example 4-2. Creating a Base58Check-encoded bitcoin address from a private key*

#include <bitcoin/bitcoin.hpp>

**int** main()

{

*// Private secret key.*

bc::ec\_secret secret = bc::decode\_hash(

"038109007313a5807b2eccc082c8c3fbb988a973cacf1a7df9ce725c31b14776");

*// Get public key.*

bc::ec\_point public\_key = bc::secret\_to\_public\_key(secret);

std::cout << "Public key: " << bc::encode\_hex(public\_key) << std::endl;

*// Create Bitcoin address.*

*// Normally you can use:*

*// bc::payment\_address payaddr;*

*// bc::set\_public\_key(payaddr, public\_key);*

*// const std::string address = payaddr.encoded();*

*// Compute hash of public key for P2PKH address.*

**const** bc::short\_hash hash = bc::bitcoin\_short\_hash(public\_key);

bc::data\_chunk unencoded\_address;

*// Reserve 25 bytes*

*// [ version:1 ]*

*// [ hash:20 ]*

*// [ checksum:4 ]*

unencoded\_address.reserve(25);

*// Version byte, 0 is normal BTC address (P2PKH).*

unencoded\_address.push\_back(0);

*// Hash data*

bc::extend\_data(unencoded\_address, hash);

*// Checksum is computed by hashing data, and adding 4 bytes from hash.*

bc::append\_checksum(unencoded\_address);

*// Finally we must encode the result in Bitcoin's base58 encoding*

assert(unencoded\_address.size() == 25);

**const** std::string address = bc::encode\_base58(unencoded\_address);

Bitcoin Addresses | 75

std::cout << "Address: " << address << std::endl;

**return** 0;

}

The code uses a predefined private key so that it produces the same bitcoin address

every time it is run, as shown in Example 4-3.

*Example 4-3. Compiling and running the addr code*

*# Compile the addr.cpp code*

$ g++ -o addr addr.cpp **$(**pkg-config --cflags --libs libbitcoin**)**

*# Run the addr executable*

$ ./addr

Public key: 0202a406624211f2abbdc68da3df929f938c3399dd79fac1b51b0e4ad1d26a47aa

Address: 1PRTTaJesdNovgne6Ehcdu1fpEdX7913CK

Key Formats

Both private and public keys can be represented in a number of different formats. These

representations all encode the same number, even though they look different. These

formats are primarily used to make it easy for people to read and transcribe keys without

introducing errors.

Private key formats

The private key can be represented in a number of different formats, all of which correspond

to the same 256-bit number. Table 4-2 shows three common formats used to

represent private keys.

*Table 4-2. Private key representations (encoding formats)*

Type Prefix Description

Hex None 64 hexadecimal digits

WIF 5 Base58Check encoding: Base58 with version prefix of 128 and 32-bit checksum

WIF-compressed K or L As above, with added suffix 0x01 before encoding

Table 4-3 shows the private key generated in these three formats.

*Table 4-3. Example: Same key, different formats*

Format Private Key

Hex 1E99423A4ED27608A15A2616A2B0E9E52CED330AC530EDCC32C8FFC6A526AEDD

WIF 5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

WIF-compressed KxFC1jmwwCoACiCAWZ3eXa96mBM6tb3TYzGmf6YwgdGWZgawvrtJ

All of these representations are different ways of showing the same number, the same

private key. They look different, but any one format can easily be converted to any other

format.

76 | Chapter 4: Keys, Addresses, Wallets

Decode from Base58Check to hex

The sx tools package (See “Libbitcoin and sx Tools” on page 56) makes it easy to write

shell scripts and command-line “pipes” that manipulate bitcoin keys, addresses, and

transactions. You can use sx tools to decode the Base58Check format on the command

line.

We use the base58check-decode command:

$ sx base58check-decode 5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

1e99423a4ed27608a15a2616a2b0e9e52ced330ac530edcc32c8ffc6a526aedd 128

The result is the hexadecimal key, followed by the Wallet Import Format (WIF) version

prefix 128.

Encode from hex to Base58Check

To encode into Base58Check (the opposite of the previous command), we provide the

hex private key, followed by the Wallet Import Format (WIF) version prefix 128:

$ sx base58check-encode

1e99423a4ed27608a15a2616a2b0e9e52ced330ac530edcc32c8ffc6a526aedd 128

5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

Encode from hex (compressed key) to Base58Check encoding

To encode into Base58Check as a “compressed” private key (see “Compressed private

keys” on page 80), we add the suffix 01 to the end of the hex key and then encode as

above:

$ sx base58check-encode

1e99423a4ed27608a15a2616a2b0e9e52ced330ac530edcc32c8ffc6a526aedd01 128

KxFC1jmwwCoACiCAWZ3eXa96mBM6tb3TYzGmf6YwgdGWZgawvrtJ

The resulting WIF-compressed format starts with a “K”. This denotes that the private

key within has a suffix of “01” and will be used to produce compressed public keys only

(see “Compressed public keys” on page 78).

Public key formats

Public keys are also presented in different ways, most importantly as either *compressed*

or *uncompressed* public keys.

As we saw previously, the public key is a point on the elliptic curve consisting of a pair

of coordinates (x,y). It is usually presented with the prefix 04 followed by two 256-bit

numbers, one for the *x* coordinate of the point, the other for the *y* coordinate. The prefix

04 is used to distinguish uncompressed public keys from compressed public keys that

begin with a 02 or a 03.

Bitcoin Addresses | 77

Here’s the public key generated by the private key we created earlier, shown as the coordinates

x and y:

x = F028892BAD7ED57D2FB57BF33081D5CFCF6F9ED3D3D7F159C2E2FFF579DC341A

y = 07CF33DA18BD734C600B96A72BBC4749D5141C90EC8AC328AE52DDFE2E505BDB

Here’s the same public key shown as a 520-bit number (130 hex digits) with the prefix

04 followed by x and then y coordinates, as 04 x y:

K = 04F028892BAD7ED57D2FB57BF33081D5CFCF6F9ED3D3D7F159C2E2FFF579DC341A<?pdf-cr?

>07CF33DA18BD734C600B96A72BBC4749D5141C90EC8AC328AE52DDFE2E505BDB

Compressed public keys

Compressed public keys were introduced to bitcoin to reduce the size of transactions

and conserve disk space on nodes that store the bitcoin blockchain database. Most

transactions include the public key, required to validate the owner’s credentials and

spend the bitcoin. Each public key requires 520 bits (prefix \+ x \+ y), which when

multiplied by several hundred transactions per block, or tens of thousands of transactions

per day, adds a significant amount of data to the blockchain.

As we saw in the section “Public Keys” on page 65, a public key is a point (x,y) on an

elliptic curve. Because the curve expresses a mathematical function, a point on the curve

represents a solution to the equation and, therefore, if we know the *x* coordinate we can

calculate the *y* coordinate by solving the equation y2 mod p = (x3 + 7) mod p. That allows

us to store only the *x* coordinate of the public key point, omitting the *y* coordinate and

reducing the size of the key and the space required to store it by 256 bits. An almost

50% reduction in size in every transaction adds up to a lot of data saved over time!

Whereas uncompressed public keys have a prefix of 04, compressed public keys start

with either a 02 or a 03 prefix. Let’s look at why there are two possible prefixes: because

the left side of the equation is y2, that means the solution for y is a square root, which

can have a positive or negative value. Visually, this means that the resulting *y* coordinate

can be above the x-axis or below the x-axis. As you can see from the graph of the elliptic

curve in Figure 4-2, the curve is symmetric, meaning it is reflected like a mirror by the

x-axis. So, while we can omit the *y* coordinate we have to store the *sign* of y (positive or

negative), or in other words, we have to remember if it was above or below the x-axis

because each of those options represents a different point and a different public key.

When calculating the elliptic curve in binary arithmetic on the finite field of prime order

p, the *y* coordinate is either even or odd, which corresponds to the positive/negative

sign as explained earlier. Therefore, to distinguish between the two possible values of y,

we store a compressed public key with the prefix 02 if the y is even, and 03 if it is odd,

allowing the software to correctly deduce the *y* coordinate from the *x* coordinate and

uncompress the public key to the full coordinates of the point. Public key compression

is illustrated in Figure 4-7.

78 | Chapter 4: Keys, Addresses, Wallets

*Figure 4-7. Public key compression*

Here’s the same public key generated previously, shown as a compressed public key

stored in 264 bits (66 hex digits) with the prefix 03 indicating the *y* coordinate is odd:

K = 03F028892BAD7ED57D2FB57BF33081D5CFCF6F9ED3D3D7F159C2E2FFF579DC341A

This compressed public key corresponds to the same private key, meaning that it is

generated from the same private key. However, it looks different from the uncompressed

public key. More importantly, if we convert this compressed public key to a bitcoin

address using the double-hash function (RIPEMD160(SHA256(K))) it will produce a

*different* bitcoin address. This can be confusing, because it means that a single private

key can produce a public key expressed in two different formats (compressed and uncompressed)

that produce two different bitcoin addresses. However, the private key is

identical for both bitcoin addresses.

Bitcoin Addresses | 79

Compressed public keys are gradually becoming the default across bitcoin clients, which

is having a significant impact on reducing the size of transactions and therefore the

blockchain. However, not all clients support compressed public keys yet. Newer clients

that support compressed public keys have to account for transactions from older clients

that do not support compressed public keys. This is especially important when a wallet

application is importing private keys from another bitcoin wallet application, because

the new wallet needs to scan the blockchain to find transactions corresponding to these

imported keys. Which bitcoin addresses should the bitcoin wallet scan for? The bitcoin

addresses produced by uncompressed public keys, or the bitcoin addresses produced

by compressed public keys? Both are valid bitcoin addresses, and can be signed for by

the private key, but they are different addresses!

To resolve this issue, when private keys are exported from a wallet, the Wallet Import

Format that is used to represent them is implemented differently in newer bitcoin wallets,

to indicate that these private keys have been used to produce *compressed* public

keys and therefore *compressed* bitcoin addresses. This allows the importing wallet to

distinguish between private keys originating from older or newer wallets and search the

blockchain for transactions with bitcoin addresses corresponding to the uncompressed,

or the compressed, public keys, respectively. Let’s look at how this works in more detail,

in the next section.

Compressed private keys

Ironically, the term “compressed private key” is misleading, because when a private key

is exported as WIF-compressed it is actually one byte *longer* than an “uncompressed”

private key. That is because it has the added 01 suffix, which signifies it comes from a

newer wallet and should only be used to produce compressed public keys. Private keys

are not compressed and cannot be compressed. The term “compressed private key”

really means “private key from which compressed public keys should be derived,”

whereas “uncompressed private key” really means “private key from which uncompressed

public keys should be derived.” You should only refer to the export format as

“WIF-compressed” or “WIF” and not refer to the private key as “compressed” to avoid

further confusion.

Remember, these formats are *not* used interchangeably. In a newer wallet that implements

compressed public keys, the private keys will only ever be exported as WIFcompressed

(with a K or L prefix). If the wallet is an older implementation and does not

use compressed public keys, the private keys will only ever be exported as WIF (with a

5 prefix). The goal here is to signal to the wallet importing these private keys whether

it must search the blockchain for compressed or uncompressed public keys and addresses.

If a bitcoin wallet is able to implement compressed public keys, it will use those in all

transactions. The private keys in the wallet will be used to derive the public key points

on the curve, which will be compressed. The compressed public keys will be used to

80 | Chapter 4: Keys, Addresses, Wallets

produce bitcoin addresses and those will be used in transactions. When exporting private

keys from a new wallet that implements compressed public keys, the Wallet Import

Format is modified, with the addition of a one-byte suffix 01 to the private key. The

resulting Base58Check-encoded private key is called a “Compressed WIF” and starts

with the letter K or L, instead of starting with “5” as is the case with WIF-encoded (noncompressed)

keys from older wallets.

Table 4-4 shows the same key, encoded in WIF and WIF-compressed formats.

*Table 4-4. Example: Same key, different formats*

Format Private Key

Hex 1E99423A4ED27608A15A2616A2B0E9E52CED330AC530EDCC32C8FFC6A526AEDD

WIF 5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

Hex-compressed 1E99423A4ED27608A15A2616A2B0E9E52CED330AC530EDCC32C8FFC6A526AEDD\_01\_

WIF-compressed KxFC1jmwwCoACiCAWZ3eXa96mBM6tb3TYzGmf6YwgdGWZgawvrtJ

“Compressed private keys” is a misnomer! They are not compressed;

rather, the WIF-compressed format signifies that they should

only be used to derive compressed public keys and their corresponding

bitcoin addresses. Ironically, a “WIF-compressed” encoded private

key is one byte longer because it has the added 01 suffix to distinguish

it from an “uncompressed” one.

Implementing Keys and Addresses in Python

The most comprehensive bitcoin library in Python is pybitcointools by Vitalik Buterin.

In Example 4-4, we use the pybitcointools library (imported as “bitcoin”) to generate

and display keys and addresses in various formats.

*Example 4-4. Key and address generation and formatting with the pybitcointools library*

**import bitcoin**

*# Generate a random private key*

valid\_private\_key = False

**while not** valid\_private\_key:

private\_key = bitcoin.random\_key()

decoded\_private\_key = bitcoin.decode\_privkey(private\_key, 'hex')

valid\_private\_key = 0 < decoded\_private\_key < bitcoin.N

**print** "Private Key (hex) is: ", private\_key

**print** "Private Key (decimal) is: ", decoded\_private\_key

*# Convert private key to WIF format*

wif\_encoded\_private\_key = bitcoin.encode\_privkey(decoded\_private\_key, 'wif')

Implementing Keys and Addresses in Python | 81

**print** "Private Key (WIF) is: ", wif\_encoded\_private\_key

*# Add suffix "01" to indicate a compressed private key*

compressed\_private\_key = private\_key + '01'

**print** "Private Key Compressed (hex) is: ", compressed\_private\_key

*# Generate a WIF format from the compressed private key (WIF-compressed)*

wif\_compressed\_private\_key = bitcoin.encode\_privkey(

bitcoin.decode\_privkey(compressed\_private\_key, 'hex'), 'wif')

**print** "Private Key (WIF-Compressed) is: ", wif\_compressed\_private\_key

*# Multiply the EC generator point G with the private key to get a public key point*

public\_key = bitcoin.base10\_multiply(bitcoin.G, decoded\_private\_key)

**print** "Public Key (x,y) coordinates is:", public\_key

*# Encode as hex, prefix 04*

hex\_encoded\_public\_key = bitcoin.encode\_pubkey(public\_key,'hex')

**print** "Public Key (hex) is:", hex\_encoded\_public\_key

*# Compress public key, adjust prefix depending on whether y is even or odd*

(public\_key\_x, public\_key\_y) = public\_key

**if** (public\_key\_y % 2) == 0:

compressed\_prefix = '02'

**else**:

compressed\_prefix = '03'

hex\_compressed\_public\_key = compressed\_prefix + bitcoin.encode(public\_key\_x, 16)

**print** "Compressed Public Key (hex) is:", hex\_compressed\_public\_key

*# Generate bitcoin address from public key*

**print** "Bitcoin Address (b58check) is:", bitcoin.pubkey\_to\_address(public\_key)

*# Generate compressed bitcoin address from compressed public key*

**print** "Compressed Bitcoin Address (b58check) is:", \

bitcoin.pubkey\_to\_address(hex\_compressed\_public\_key)

Example 4-5 shows the output from running this code.

*Example 4-5. Running key-to-address-ecc-example.py*

$ python key-to-address-ecc-example.py

Private Key (hex) is:

3aba4162c7251c891207b747840551a71939b0de081f85c4e44cf7c13e41daa6

Private Key (decimal) is:

26563230048437957592232553826663696440606756685920117476832299673293013768870

Private Key (WIF) is:

5JG9hT3beGTJuUAmCQEmNaxAuMacCTfXuw1R3FCXig23RQHMr4K

Private Key Compressed (hex) is:

3aba4162c7251c891207b747840551a71939b0de081f85c4e44cf7c13e41daa601

Private Key (WIF-Compressed) is:

KyBsPXxTuVD82av65KZkrGrWi5qLMah5SdNq6uftawDbgKa2wv6S

Public Key (x,y) coordinates is:

(41637322786646325214887832269588396900663353932545912953362782457239403430124L,

16388935128781238405526710466724741593761085120864331449066658622400339362166L)

82 | Chapter 4: Keys, Addresses, Wallets

Public Key (hex) is:

045c0de3b9c8ab18dd04e3511243ec2952002dbfadc864b9628910169d9b9b00ec↵

243bcefdd4347074d44bd7356d6a53c495737dd96295e2a9374bf5f02ebfc176

Compressed Public Key (hex) is:

025c0de3b9c8ab18dd04e3511243ec2952002dbfadc864b9628910169d9b9b00ec

Bitcoin Address (b58check) is:

1thMirt546nngXqyPEz532S8fLwbozud8

Compressed Bitcoin Address (b58check) is:

14cxpo3MBCYYWCgF74SWTdcmxipnGUsPw3

Example 4-6 is another example, using the Python ECDSA library for the elliptic curve

math and without using any specialized bitcoin libraries.

*Example 4-6. A script demonstrating elliptic curve math used for bitcoin keys*

**import ecdsa**

**import random**

**from ecdsa.util import** string\_to\_number, number\_to\_string

*# secp256k1, http://www.oid-info.com/get/1.3.132.0.10*

\_p = 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFEFFFFFC2FL

\_r = 0xFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFEBAAEDCE6AF48A03BBFD25E8CD0364141L

\_b = 0x0000000000000000000000000000000000000000000000000000000000000007L

\_a = 0x0000000000000000000000000000000000000000000000000000000000000000L

\_Gx = 0x79BE667EF9DCBBAC55A06295CE870B07029BFCDB2DCE28D959F2815B16F81798L

\_Gy = 0x483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8L

curve\_secp256k1 = ecdsa.ellipticcurve.CurveFp(\_p, \_a, \_b)

generator\_secp256k1 = ecdsa.ellipticcurve.Point(curve\_secp256k1, \_Gx, \_Gy, \_r)

oid\_secp256k1 = (1, 3, 132, 0, 10)

SECP256k1 = ecdsa.curves.Curve("SECP256k1", curve\_secp256k1, generator\_secp256k1,

oid\_secp256k1)

ec\_order = \_r

curve = curve\_secp256k1

generator = generator\_secp256k1

**def** random\_secret():

random\_char = **lambda**: chr(random.randint(0, 255))

convert\_to\_int = **lambda** array: int("".join(array).encode("hex"), 16)

byte\_array = [random\_char() **for** i **in** range(32)]

**return** convert\_to\_int(byte\_array)

**def** get\_point\_pubkey(point):

**if** point.y() & 1:

key = '03' + '%064x' % point.x()

**else**:

key = '02' + '%064x' % point.x()

**return** key.decode('hex')

**def** get\_point\_pubkey\_uncompressed(point):

key = '04' + \

'%064x' % point.x() + \

Implementing Keys and Addresses in Python | 83

'%064x' % point.y()

**return** key.decode('hex')

*# Generate a new private key.*

secret = random\_secret()

**print** "Secret: ", secret

*# Get the public key point.*

point = secret \* generator

**print** "EC point:", point

**print** "BTC public key:", get\_point\_pubkey(point).encode("hex")

*# Given the point (x, y) we can create the object using:*

point1 = ecdsa.ellipticcurve.Point(curve, point.x(), point.y(), ec\_order)

**assert** point1 == point

Example 4-7 shows the output produced by running this script.

*Example 4-7. Installing the Python ECDSA library and running the ec\_math.py script*

$ # Install Python PIP package manager

$ sudo apt-get install python-pip

$ # Install the Python ECDSA library

$ sudo pip install ecdsa

$ # Run the script

$ python ec-math.py

Secret:

38090835015954358862481132628887443905906204995912378278060168703580660294000

EC point:

(70048853531867179489857750497606966272382583471322935454624595540007269312627,

105262206478686743191060800263479589329920209527285803935736021686045542353380)

BTC public key: 029ade3effb0a67d5c8609850d797366af428f4a0d5194cb221d807770a1522873

Wallets

Wallets are containers for private keys, usually implemented as structured files or simple

databases. Another method for making keys is *deterministic key generation*. Here you

derive each new private key, using a one-way hash function from a previous private key,

linking them in a sequence. As long as you can re-create that sequence, you only need

the first key (known as a *seed* or *master* key) to generate them all. In this section we will

examine the different methods of key generation and the wallet structures that are built

around them.

84 | Chapter 4: Keys, Addresses, Wallets

Bitcoin wallets contain keys, not coins. Each user has a wallet containing

keys. Wallets are really keychains containing pairs of private/

public keys (see “Private and Public Keys” on page 63). Users sign

transactions with the keys, thereby proving they own the transaction

outputs (their coins). The coins are stored on the blockchain in

the form of transaction-ouputs (often noted as vout or txout).

Nondeterministic (Random) Wallets

In the first bitcoin clients, wallets were simply collections of randomly generated private

keys. This type of wallet is called a *Type-0 nondeterministic wallet*. For example, the

Bitcoin Core client pregenerates 100 random private keys when first started and generates

more keys as needed, using each key only once. This type of wallet is nicknamed

“Just a Bunch Of Keys,” or JBOK, and such wallets are being replaced with deterministic

wallets because they are cumbersome to manage, back up, and import. The disadvantage

of random keys is that if you generate many of them you must keep copies of all of them,

meaning that the wallet must be backed up frequently. Each key must be backed up, or

the funds it controls are irrevocably lost if the wallet becomes inaccessible. This conflicts

directly with the principle of avoiding address re-use, by using each bitcoin address for

only one transaction. Address re-use reduces privacy by associating multiple transactions

and addresses with each other. A Type-0 nondeterministic wallet is a poor choice

of wallet, especially if you want to avoid address re-use because that means managing

many keys, which creates the need for frequent backups. Although the Bitcoin Core

client includes a Type-0 wallet, using this wallet is discouraged by developers of Bitcoin

Core. Figure 4-8 shows a nondeterministic wallet, containing a loose collection of random

keys.

Deterministic (Seeded) Wallets

Deterministic, or “seeded” wallets are wallets that contain private keys that are all derived

from a common seed, through the use of a one-way hash function. The seed is a randomly

generated number that is combined with other data, such as an index number

or “chain code” (see “Hierarchical Deterministic Wallets (BIP0032/BIP0044)” on page

87) to derive the private keys. In a deterministic wallet, the seed is sufficient to recover

all the derived keys, and therefore a single backup at creation time is sufficient. The seed

is also sufficient for a wallet export or import, allowing for easy migration of all the user’s

keys between different wallet implementations.

Wallets | 85

*Figure 4-8. Type-0 nondeterministic (random) wallet: a collection of randomly generated*

*keys*

Mnemonic Code Words

Mnemonic codes are English word sequences that represent (encode) a random number

used as a seed to derive a deterministic wallet. The sequence of words is sufficient to recreate

the seed and from there re-create the wallet and all the derived keys. A wallet

application that implements deterministic wallets with mnemonic code will show the

user a sequence of 12 to 24 words when first creating a wallet. That sequence of words

is the wallet backup and can be used to recover and re-create all the keys in the same or

any compatible wallet application. Mnemonic code words make it easier for users to

back up wallets because they are easy to read and correctly transcribe, as compared to

a random sequence of numbers.

Mnemonic codes are defined in Bitcoin Improvement Proposal 39 (see [bip0039]),

currently in Draft status. Note that BIP0039 is a draft proposal and not a standard.

Specifically, there is a different standard, with a different set of words, used by the

Electrum wallet and predating BIP0039. BIP0039 is used by the Trezor wallet and a few

other wallets but is incompatible with Electrum’s implementation.

BIP0039 defines the creation of a mnemonic code and seed as a follows:

1. Create a random sequence (entropy) of 128 to 256 bits.

2. Create a checksum of the random sequence by taking the first few bits of its SHA256

hash.

86 | Chapter 4: Keys, Addresses, Wallets

3. Add the checksum to the end of the random sequence.

4. Divide the sequence into sections of 11 bits, using those to index a dictionary of

2048 predefined words.

5. Produce 12 to 24 words representing the mnemonic code.

Table 4-5 shows the relationship between the size of entropy data and the length of

mnemonic codes in words.

*Table 4-5. Mnemonic codes: entropy and word length*

Entropy (bits) Checksum (bits) Entropy+checksum Word length

128 4 132 12

160 5 165 15

192 6 198 18

224 7 231 21

256 8 264 24

The mnemonic code represents 128 to 256 bits, which are used to derive a longer (512-

bit) seed through the use of the key-stretching function PBKDF2. The resulting seed is

used to create a deterministic wallet and all of its derived keys.

Tables 4-6 and 4-7 show some examples of mnemonic codes and the seeds they produce.

*Table 4-6. 128-bit entropy mnemonic code and resulting seed*

**Entropy input (128**

**bits)**

0c1e24e5917779d297e14d45f14e1a1a

**Mnemonic (12**

**words)**

army van defense carry jealous true garbage claim echo media make crunch

**Seed (512 bits)** 3338a6d2ee71c7f28eb5b882159634cd46a898463e9d2d0980f8e80dfbba5b0fa0291e5fb88

8a599b44b93187be6ee3ab5fd3ead7dd646341b2cdb8d08d13bf7

*Table 4-7. 256-bit entropy mnemonic code and resulting seed*

**Entropy input**

**(256 bits)**

2041546864449caff939d32d574753fe684d3c947c3346713dd8423e74abcf8c

**Mnemonic (24**

**words)**

cake apple borrow silk endorse fitness top denial coil riot stay wolf luggage oxygen faint major edit measure

invite love trap field dilemma oblige

**Seed (512 bits)** 3972e432e99040f75ebe13a660110c3e29d131a2c808c7ee5f1631d0a977fcf473bee22

fce540af281bf7cdeade0dd2c1c795bd02f1e4049e205a0158906c343

Hierarchical Deterministic Wallets (BIP0032/BIP0044)

Deterministic wallets were developed to make it easy to derive many keys from a single

“seed.” The most advanced form of deterministic wallets is the *hierarchical deterministic*

Wallets | 87

*wallet* or *HD wallet* defined by the BIP0032 standard. Hierarchical deterministic wallets

contain keys derived in a tree structure, such that a parent key can derive a sequence of

children keys, each of which can derive a sequence of grandchildren keys, and so on, to

an infinite depth. This tree structure is illustrated in Figure 4-9.

*Figure 4-9. Type-2 hierarchical deterministic wallet: a tree of keys generated from a*

*seed*

If you are implementing a bitcoin wallet, it should be built as an HD

wallet following the BIP0032 and BIP0044 standards.

HD wallets offer two major advantages over random (nondeterministic) keys. First, the

tree structure can be used to express additional organizational meaning, such as when

a specific branch of subkeys is used to receive incoming payments and a different branch

is used to receive change from outgoing payments. Branches of keys can also be used

in a corporate setting, allocating different branches to departments, subsidiaries, specific

functions, or accounting categories.

The second advantage of HD wallets is that users can create a sequence of public keys

without having access to the corresponding private keys. This allows HD wallets to be

used on an insecure server or in a receive-only capacity, issuing a different public key

for each transaction. The public keys do not need to be preloaded or derived in advance,

yet the server doesn’t have the private keys that can spend the funds.

88 | Chapter 4: Keys, Addresses, Wallets

HD wallet creation from a seed

HD wallets are created from a single *root seed*, which is a 128-, 256-, or 512-bit random

number. Everything else in the HD wallet is deterministically derived from this root

seed, which makes it possible to re-create the entire HD wallet from that seed in any

compatible HD wallet. This makes it easy to back up, restore, export, and import HD

wallets containing thousands or even millions of keys by simply transferring only the

root seed. The root seed is most often represented by a *mnemonic word sequence*, as

described in the previous section “Mnemonic Code Words” on page 86, to make it easier

for people to transcribe and store it.

The process of creating the master keys and master chain code for an HD wallet is shown

in Figure 4-10.

*Figure 4-10. Creating master keys and chain code from a root seed*

The root seed is input into the HMAC-SHA512 algorithm and the resulting hash is used

to create a *master private key* (m) and a *master chain code*. The master private key (m)

then generates a corresponding master public key (M), using the normal elliptic curve

multiplication process m \* G that we saw earlier in this chapter. The chain code is used

to introduce entropy in the function that creates child keys from parent keys, as we will

see in the next section.

Private child key derivation

Hierarchical deterministic wallets use a *child key derivation* (CKD) function to derive

children keys from parent keys.

The child key derivation functions are based on a one-way hash function that combines:

• A parent private or public key (ECDSA uncompressed key)

• A seed called a chain code (256 bits)

Wallets | 89

• An index number (32 bits)

The chain code is used to introduce seemingly random data to the process, so that the

index is not sufficient to derive other child keys. Thus, having a child key does not make

it possible to find its siblings, unless you also have the chain code. The initial chain code

seed (at the root of the tree) is made from random data, while subsequent chain codes

are derived from each parent chain code.

These three items are combined and hashed to generate children keys, as follows.

The parent public key, chain code, and the index number are combined and hashed

with the HMAC-SHA512 algorithm to produce a 512-bit hash. The resulting hash is

split into two halves. The right-half 256 bits of the hash output become the chain code

for the child. The left-half 256 bits of the hash and the index number are added to the

parent private key to produce the child private key. In Figure 4-11, we see this illustrated

with the index set to 0 to produce the 0’th (first by index) child of the parent.

*Figure 4-11. Extending a parent private key to create a child private key*

Changing the index allows us to extend the parent and create the other children in the

sequence, e.g., Child 0, Child 1, Child 2, etc. Each parent key can have 2 billion children

keys.

Repeating the process one level down the tree, each child can in turn become a parent

and create its own children, in an infinite number of generations.

90 | Chapter 4: Keys, Addresses, Wallets

Using derived child keys

Child private keys are indistinguishable from nondeterministic (random) keys. Because

the derivation function is a one-way function, the child key cannot be used to find the

parent key. The child key also cannot be used to find any siblings. If you have the nth

child, you cannot find its siblings, such as the n–1 child or the n+1 child, or any other

children that are part of the sequence. Only the parent key and chain code can derive

all the children. Without the child chain code, the child key cannot be used to derive

any grandchildren either. You need both the child private key and the child chain code

to start a new branch and derive grandchildren.

So what can the child private key be used for on its own? It can be used to make a public

key and a bitcoin address. Then, it can be used to sign transactions to spend anything

paid to that address.

A child private key, the corresponding public key, and the bitcoin

address are all indistinguishable from keys and addresses created

randomly. The fact that they are part of a sequence is not visible,

outside of the HD wallet function that created them. Once created,

they operate exactly as “normal” keys.

Extended keys

As we saw earlier, the key derivation function can be used to create children at any level

of the tree, based on the three inputs: a key, a chain code, and the index of the desired

child. The two essential ingredients are the key and chain code, and combined these are

called an *extended key*. The term “extended key” could also be thought of as “extensible

key” because such a key can be used to derive children.

Extended keys are stored and represented simply as the concatenation of the 256-bit

key and 256-bit chain code into a 512-bit sequence. There are two types of extended

keys. An extended private key is the combination of a private key and chain code and

can be used to derive child private keys (and from them, child public keys). An extended

public key is a public key and chain code, which can be used to create child public keys,

as described in “Generating a Public Key” on page 68.

Think of an extended key as the root of a branch in the tree structure of the HD wallet.

With the root of the branch, you can derive the rest of the branch. The extended private

key can create a complete branch, whereas the extended public key can only create a

branch of public keys.

Wallets | 91

An extended key consists of a private or public key and chain code.

An extended key can create children, generating its own branch in

the tree structure. Sharing an extended key gives access to the entire

branch.

Extended keys are encoded using Base58Check, to easily export and import between

different BIP0032-compatible wallets. The Base58Check coding for extended keys uses

a special version number that results in the prefix “xprv” and “xpub” when encoded in

Base58 characters, to make them easily recognizable. Because the extended key is 512

or 513 bits, it is also much longer than other Base58Check-encoded strings we have seen

previously.

Here’s an example of an extended private key, encoded in Base58Check:

xprv9tyUQV64JT5qs3RSTJkXCWKMyUgoQp7F3hA1xzG6ZGu6u6Q9VMNjGr67Lctvy5P8oyaYAL9CAWrUE9i6GoNMKUga5biW6Hx4tws2six3b9c

Here’s the corresponding extended public key, also encoded in Base58Check:

xpub67xpozcx8pe95XVuZLHXZeG6XWXHpGq6Qv5cmNfi7cS5mtjJ2tgypeQbBs2UAR6KECeeMVKZBPLrtJunSDMstweyLXhRgPxdp14sk9tJPW9

Public child key derivation

As mentioned previously, a very useful characteristic of hierarchical deterministic wallets

is the ability to derive public child keys from public parent keys, *without* having the

private keys. This gives us two ways to derive a child public key: either from the child

private key, or directly from the parent public key.

An extended public key can be used, therefore, to derive all of the *public* keys (and only

the public keys) in that branch of the HD wallet structure.

This shortcut can be used to create very secure public-key-only deployments where a

server or application has a copy of an extended public key and no private keys whatsoever.

That kind of deployment can produce an infinite number of public keys and bitcoin

addresses, but cannot spend any of the money sent to those addresses. Meanwhile, on

another, more secure server, the extended private key can derive all the corresponding

private keys to sign transactions and spend the money.

One common application of this solution is to install an extended public key on a web

server that serves an ecommerce application. The web server can use the public key

derivation function to create a new bitcoin address for every transaction (e.g., for a

customer shopping cart). The web server will not have any private keys that would be

vulnerable to theft. Without HD wallets, the only way to do this is to generate thousands

of bitcoin addresses on a separate secure server and then preload them on the ecom‐

92 | Chapter 4: Keys, Addresses, Wallets

merce server. That approach is cumbersome and requires constant maintenance to ensure

that the ecommerce server doesn’t “run out” of keys.

Another common application of this solution is for cold-storage or hardware wallets.

In that scenario, the extended private key can be stored on a paper wallet or hardware

device (such as a Trezor hardware wallet), while the extended public key can be kept

online. The user can create “receive” addresses at will, while the private keys are safely

stored offline. To spend the funds, the user can use the extended private key on an offline

signing bitcoin client or sign transactions on the hardware wallet device (e.g., Trezor).

Figure 4-12 illustrates the mechanism for extending a parent public key to derive child

public keys.

*Figure 4-12. Extending a parent public key to create a child public key*

Hardened child key derivation

The ability to derive a branch of public keys from an extended public key is very useful,

but it comes with a potential risk. Access to an extended public key does not give access

to child private keys. However, because the extended public key contains the chain code,

if a child private key is known, or somehow leaked, it can be used with the chain code

to derive all the other child private keys. A single leaked child private key, together with

a parent chain code, reveals all the private keys of all the children. Worse, the child

private key together with a parent chain code can be used to deduce the parent private

key.

To counter this risk, HD wallets use an alternative derivation function called *hardened*

*derivation*, which “breaks” the relationship between parent public key and child chain

code. The hardened derivation function uses the parent private key to derive the child

chain code, instead of the parent public key. This creates a “firewall” in the parent/child

sequence, with a chain code that cannot be used to compromise a parent or sibling

private key. The hardened derivation function looks almost identical to the normal child

Wallets | 93

private key derivation, except that the parent private key is used as input to the hash

function, instead of the parent public key, as shown in the diagram in Figure 4-13.

*Figure 4-13. Hardened derivation of a child key; omits the parent public key*

When the hardened private derivation function is used, the resulting child private key

and chain code are completely different from what would result from the normal derivation

function. The resulting “branch” of keys can be used to produce extended public

keys that are not vulnerable, because the chain code they contain cannot be exploited

to reveal any private keys. Hardened derivation is therefore used to create a “gap” in the

tree above the level where extended public keys are used.

In simple terms, if you want to use the convenience of an extended public key to derive

branches of public keys, without exposing yourself to the risk of a leaked chain code,

you should derive it from a hardened parent, rather than a normal parent. As a best

practice, the level-1 children of the master keys are always derived through the hardened

derivation, to prevent compromise of the master keys.

Index numbers for normal and hardened derivation

The index number used in the derivation function is a 32-bit integer. To easily distinguish

between keys derived through the normal derivation function versus keys derived

through hardened derivation, this index number is split into two ranges. Index numbers

between 0 and 231–1 (0x0 to 0x7FFFFFFF) are used *only* for normal derivation. Index

numbers between 231 and 232–1 (0x80000000 to 0xFFFFFFFF) are used *only* for hardened

94 | Chapter 4: Keys, Addresses, Wallets

derivation. Therefore, if the index number is less than 231, that means the child is normal,

whereas if the index number is equal or above 231, the child is hardened.

To make the index number easier to read and display, the index number for hardened

children is displayed starting from zero, but with a prime symbol. The first normal child

key is therefore displayed as 0, whereas the first hardened child (index 0x80000000) is

displayed as 0'. In sequence then, the second hardened key would have index

0x80000001 and would be displayed as 1', and so on. When you see an HD wallet index

i', that means 231+i.

HD wallet key identifier (path)

Keys in an HD wallet are identified using a “path” naming convention, with each level

of the tree separated by a slash (/) character (see Table 4-8). Private keys derived from

the master private key start with “m”. Public keys derived from the master public key

start with “M”. Therefore, the first child private key of the master private key is m/0. The

first child public key is M/0. The second grandchild of the first child is m/0/1, and so

on.

The “ancestry” of a key is read from right to left, until you reach the master key from

which it was derived. For example, identifier m/x/y/z describes the key that is the z-th

child of key m/x/y, which is the y-th child of key m/x, which is the x-th child of m.

*Table 4-8. HD wallet path examples*

HD path Key described

m/0 The first (0) child private key from the master private key (m)

m/0/0 The first grandchild private key of the first child (m/0)

m/0'/0 The first normal grandchild of the first *hardened* child (m/0')

m/1/0 The first grandchild private key of the second child (m/1)

M/23/17/0/0 The first great-great-grandchild public key of the first great-grandchild of the 18th grandchild of the 24th child

Navigating the HD wallet tree structure

The HD wallet tree structure offers tremendous flexibility. Each parent extended key

can have 4 billion children: 2 billion normal children and 2 billion hardened children.

Each of those children can have another 4 billion children, and so on. The tree can be

as deep as you want, with an infinite number of generations. With all that flexibility,

however, it becomes quite difficult to navigate this infinite tree. It is especially difficult

to transfer HD wallets between implementations, because the possibilities for internal

organization into branches and subbranches are endless.

Two Bitcoin Improvement Proposals (BIPs) offer a solution to this complexity, by creating

some proposed standards for the structure of HD wallet trees. BIP0043 proposes

the use of the first hardened child index as a special identifier that signifies the “purpose”

of the tree structure. Based on BIP0043, an HD wallet should use only one level-1 branch

Wallets | 95

of the tree, with the index number identifying the structure and namespace of the rest

of the tree by defining its purpose. For example, an HD wallet using only branch m/i'/

is intended to signify a specific purpose and that purpose is identified by index number

“i”.

Extending that specification, BIP0044 proposes a multiaccount structure as “purpose”

number 44' under BIP0043. All HD wallets following the BIP0044 structure are identified

by the fact that they only used one branch of the tree: m/44'/.

BIP0044 specifies the structure as consisting of five predefined tree levels:

m / purpose' / coin\_type' / account' / change / address\_index

The first-level “purpose” is always set to 44'. The second-level “coin\_type” specifies the

type of cryptocurrency coin, allowing for multicurrency HD wallets where each currency

has its own subtree under the second level. There are three currencies defined for

now: Bitcoin is m/44'/0', Bitcoin Testnet is m/44'/1'; and Litecoin is m/44'/2'.

The third level of the tree is “account,” which allows users to subdivide their wallets into

separate logical subaccounts, for accounting or organizational purposes. For example,

an HD wallet might contain two bitcoin “accounts”: m/44'/0'/0' and m/44'/0'/1'. Each

account is the root of its own subtree.

On the fourth level, “change,” an HD wallet has two subtrees, one for creating receiving

addresses and one for creating change addresses. Note that whereas the previous levels

used hardened derivation, this level uses normal derivation. This is to allow this level

of the tree to export extended public keys for use in a nonsecured environment. Usable

addresses are derived by the HD wallet as children of the fourth level, making the fifth

level of the tree the “address\_index.” For example, the third receiving address for bitcoin

payments in the primary account would be M/44'/0'/0'/0/2. Table 4-9 shows a few more

examples.

*Table 4-9. BIP0044 HD wallet structure examples*

HD path Key described

M/44'/0'/0'/0/2 The third receiving public key for the primary bitcoin account

M/44'/0'/3'/1/14 The fifteenth change-address public key for the fourth bitcoin account

m/44'/2'/0'/0/1 The second private key in the Litecoin main account, for signing transactions

Experimenting with HD wallets using sx tools

Using the command-line tool sx, introduced in Chapter 3, you can experiment with

generating and extending BIP0032 deterministic keys, as well as displaying them in

different formats:

$ sx hd-seed > m *# create a new master private key from a seed and store in*

*file "m"*

$ cat m *# show the master extended private key*

96 | Chapter 4: Keys, Addresses, Wallets

xprv9s21ZrQH143K38iQ9Y5p6qoB8C75TE71NfpyQPdfGvzghDt39DHPFpovvtWZaRgY5uPwV7RpEgHs7cvdgfiSjLjjbuGKGcjRyU7RGGSS8Xa

$ cat m | sx hd-pub 0 *# generate the M/0 extended public key*

xpub67xpozcx8pe95XVuZLHXZeG6XWXHpGq6Qv5cmNfi7cS5mtjJ2tgypeQbBs2UAR6KECeeMVKZBPLrtJunSDMstweyLXhRgPxdp14sk9tJPW9

$ cat m | sx hd-priv 0 *# generate the m/0 extended private key*

xprv9tyUQV64JT5qs3RSTJkXCWKMyUgoQp7F3hA1xzG6ZGu6u6Q9VMNjGr67Lctvy5P8oyaYAL9CAWrUE9i6GoNMKUga5biW6Hx4tws2six3b9c

$ cat m | sx hd-priv 0 | sx hd-to-wif *# show the private key of m/0 as a WIF*

L1pbvV86crAGoDzqmgY85xURkz3c435Z9nirMt52UbnGjYMzKBUN

$ cat m | sx hd-pub 0 | sx hd-to-address *# show the bitcoin address of M/0*

1CHCnCjgMNb6digimckNQ6TBVcTWBAmPHK

$ cat m | sx hd-priv 0 | sx hd-priv 12 --hard | sx hd-priv 4 *# generate m/*

*0/12'/4*

xprv9yL8ndfdPVeDWJenF18oiHguRUj8jHmVrqqD97YQHeTcR3LCeh53q5PXPkLsy2kRaqgwoS6YZBLatRZRyUeAkRPe1kLR1P6Mn7jUrXFquUt

Advanced Keys and Addresses

In the following sections we will look at advanced forms of keys and addresses, such as

encrypted private keys, script and multisignature addresses, vanity addresses, and paper

wallets.

Encrypted Private Keys (BIP0038)

Private keys must remain secret. The need for *confidentiality* of the private keys is a

truism that is quite difficult to achieve in practice, because it conflicts with the equally

important security objective of *availability*. Keeping the private key private is much

harder when you need to store backups of the private key to avoid losing it. A private

key stored in a wallet that is encrypted by a password might be secure, but that wallet

needs to be backed up. At times, users need to move keys from one wallet to another—

to upgrade or replace the wallet software, for example. Private key backups might also

be stored on paper (see “Paper Wallets” on page 104) or on external storage media, such

as a USB flash drive. But what if the backup itself is stolen or lost? These conflicting

security goals led to the introduction of a portable and convenient standard for encrypting

private keys in a way that can be understood by many different wallets and

bitcoin clients, standardized by Bitcoin Improvement Proposal 38 or BIP0038 (see

[bip0038]).

BIP0038 proposes a common standard for encrypting private keys with a passphrase

and encoding them with Base58Check so that they can be stored securely on backup

media, transported securely between wallets, or kept in any other conditions where the

key might be exposed. The standard for encryption uses the Advanced Encryption

Standard (AES), a standard established by the National Institute of Standards and

Technology (NIST) and used broadly in data encryption implementations for commercial

and military applications.

Advanced Keys and Addresses | 97

A BIP0038 encryption scheme takes as input a bitcoin private key, usually encoded in

the Wallet Import Format (WIF), as a Base58Check string with a prefix of “5”. Additionally,

the BIP0038 encryption scheme takes a passphrase—a long password—usually

composed of several words or a complex string of alphanumeric characters. The result

of the BIP0038 encryption scheme is a Base58Check-encoded encrypted private key

that begins with the prefix 6P. If you see a key that starts with 6P, that means it is

encrypted and requires a passphrase in order to convert (decrypt) it back into a WIFformatted

private key (prefix 5) that can be used in any wallet. Many wallet applications

now recognize BIP0038-encrypted private keys and will prompt the user for a passphrase

to decrypt and import the key. Third-party applications, such as the incredibly

useful browser-based Bit Address (Wallet Details tab), can be used to decrypt BIP0038

keys.

The most common use case for BIP0038 encrypted keys is for paper wallets that can be

used to back up private keys on a piece of paper. As long as the user selects a strong

passphrase, a paper wallet with BIP0038 encrypted private keys is incredibly secure and

a great way to create offline bitcoin storage (also known as “cold storage”).

Test the encrypted keys in Table 4-10 using bitaddress.org to see how you can get the

decrypted key by entering the passphrase.

*Table 4-10. Example of BIP0038 encrypted private key*

**Private Key (WIF)** 5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

**Passphrase** MyTestPassphrase

**Encrypted Key (BIP0038)** 6PRTHL6mWa48xSopbU1cKrVjpKbBZxcLRRCdctLJ3z5yxE87MobKoXdTsJ

Pay-to-Script Hash (P2SH) and Multi-Sig Addresses

As we know, traditional bitcoin addresses begin with the number “1” and are derived

from the public key, which is derived from the private key. Although anyone can send

bitcoin to a “1” address, that bitcoin can only be spent by presenting the corresponding

private key signature and public key hash.

Bitcoin addresses that begin with the number “3” are pay-to-script hash (P2SH) addresses,

sometimes erroneously called multi-signature or multi-sig addresses. They

designate the beneficiary of a bitcoin transaction as the hash of a script, instead of the

owner of a public key. The feature was introduced in January 2012 with Bitcoin Improvement

Proposal 16, or BIP0016 (see [bip0016]), and is being widely adopted because

it provides the opportunity to add functionality to the address itself. Unlike transactions

that “send” funds to traditional “1” bitcoin addresses, also known as pay-topublic-

key-hash (P2PKH), funds sent to “3” addresses require something more than

the presentation of one public key hash and one private key signature as proof of ownership.

The requirements are designated at the time the address is created, within the

script, and all inputs to this address will be encumbered with the same requirements.

98 | Chapter 4: Keys, Addresses, Wallets

A pay-to-script hash address is created from a transaction script, which defines who

can spend a transaction output (for more detail, see “Pay-to-Script-Hash (P2SH)” on

page 132). Encoding a pay-to-script hash address involves using the same double-hash

function as used during creation of a bitcoin address, only applied on the script instead

of the public key:

script hash = RIPEMD160(SHA256(script))

The resulting “script hash” is encoded with Base58Check with a version prefix of 5,

which results in an encoded address starting with a 3. An example of a P2SH address is

32M8ednmuyZ2zVbes4puqe44NZumgG92sM.

P2SH is not necessarily the same as a multi-signature standard transaction.

A P2SH address *most often* represents a multi-signature script,

but it might also represent a script encoding other types of transactions.

Multi-signature addresses and P2SH

Currently, the most common implementation of the P2SH function is the multisignature

address script. As the name implies, the underlying script requires more than

one signature to prove ownership and therefore spend funds. The bitcoin multisignature

feature is designed to require M signatures (also known as the “threshold”)

from a total of N keys, known as an M-of-N multi-sig, where M is equal to or less than

N. For example, Bob the coffee shop owner from Chapter 1 could use a multi-signature

address requiring 1-of-2 signatures from a key belonging to him and a key belonging

to his spouse, ensuring either of them could sign to spend a transaction output locked

to this address. This would be similar to a “joint account” as implemented in traditional

banking where either spouse can spend with a single signature. Or Gopesh, the web

designer paid by Bob to create a website, might have a 2-of-3 multi-signature address

for his business that ensures that no funds can be spent unless at least two of the business

partners sign a transaction.

We will explore how to create transactions that spend funds from P2SH (and multisignature)

addresses in Chapter 5.

Vanity Addresses

Vanity addresses are valid bitcoin addresses that contain human-readable messages. For

example, 1LoveBPzzD72PUXLzCkYAtGFYmK5vYNR33 is a valid address that contains the

letters forming the word “Love” as the first four Base-58 letters. Vanity addresses require

generating and testing billions of candidate private keys, until one derives a bitcoin

address with the desired pattern. Although there are some optimizations in the vanity

generation algorithm, the process essentially involves picking a private key at random,

Advanced Keys and Addresses | 99

deriving the public key, deriving the bitcoin address, and checking to see if it matches

the desired vanity pattern, repeating billions of times until a match is found.

Once a vanity address matching the desired pattern is found, the private key from which

it was derived can be used by the owner to spend bitcoins in exactly the same way as

any other address. Vanity addresses are no less or more secure than any other address.

They depend on the same Elliptic Curve Cryptography (ECC) and Secure Hash Algorithm

(SHA) as any other address. You can no more easily find the private key of an

address starting with a vanity pattern than you can any other address.

In Chapter 1, we introduced Eugenia, a children’s charity director operating in the Philippines.

Let’s say that Eugenia is organizing a bitcoin fundraising drive and wants to use

a vanity bitcoin address to publicize the fundraising. Eugenia will create a vanity address

that starts with “1Kids” to promote the children’s charity fundraiser. Let’s see how this

vanity address will be created and what it means for the security of Eugenia’s charity.

Generating vanity addresses

It’s important to realize that a bitcoin address is simply a number represented by symbols

in the Base58 alphabet. The search for a pattern like “1Kids” can be seen as searching

for an address in the range from 1Kids11111111111111111111111111111 to

1Kidszzzzzzzzzzzzzzzzzzzzzzzzzzzzz. There are approximately 5829 (approximately

1.4 \* 1051) addresses in that range, all starting with “1Kids”. Table 4-11 shows the range

of addresses that have the prefix 1Kids.

*Table 4-11. The range of vanity addresses starting with “1Kids”*

**From** 1Kids11111111111111111111111111111

**To** 1Kidszzzzzzzzzzzzzzzzzzzzzzzzzzzzz

Let’s look at the pattern “1Kids” as a number and see how frequently we might find this

pattern in a bitcoin address (see Table 4-12). An average desktop computer PC, without

any specialized hardware, can search approximately 100,000 keys per second.

*Table 4-12. The frequency of a vanity pattern (1KidsCharity) and average time-to-find*

*on a desktop PC*

Length Pattern Frequency Average search time

1 1K 1 in 58 keys < 1 milliseconds

2 1Ki 1 in 3,364 50 milliseconds

3 1Kid 1 in 195,000 < 2 seconds

4 1Kids 1 in 11 million 1 minute

5 1KidsC 1 in 656 million 1 hour

6 1KidsCh 1 in 38 billion 2 days

7 1KidsCha 1 in 2.2 trillion 3–4 months

100 | Chapter 4: Keys, Addresses, Wallets

Length Pattern Frequency Average search time

8 1KidsChar 1 in 128 trillion 13–18 years

9 1KidsChari 1 in 7 quadrillion 800 years

10 1KidsCharit 1 in 400 quadrillion 46,000 years

11 1KidsCharity 1 in 23 quintillion 2.5 million years

As you can see, Eugenia won’t be creating the vanity address “1KidsCharity” any time

soon, even if she had access to several thousand computers. Each additional character

increases the difficulty by a factor of 58. Patterns with more than seven characters are

usually found by specialized hardware, such as custom-built desktops with multiple

graphical processing units (GPUs). These are often repurposed bitcoin mining “rigs”

that are no longer profitable for bitcoin mining but can be used to find vanity addresses.

Vanity searches on GPU systems are many orders of magnitude faster than on a generalpurpose

CPU.

Another way to find a vanity address is to outsource the work to a pool of vanity miners,

such as the pool at Vanity Pool. A pool is a service that allows those with GPU hardware

to earn bitcoin searching for vanity addresses for others. For a small payment (0.01

bitcoin or approximately $5 at the time of this writing), Eugenia can outsource the search

for a seven-character pattern vanity address and get results in a few hours instead of

having to run a CPU search for months.

Generating a vanity address is a brute-force exercise: try a random key, check the resulting

address to see if it matches the desired pattern, repeat until successful.

Example 4-8 shows an example of a “vanity miner,” a program designed to find vanity

addresses, written in C++. The example uses the libbitcoin library, which we introduced

in “Alternative Clients, Libraries, and Toolkits” on page 56.

*Example 4-8. Vanity address miner*

#include <bitcoin/bitcoin.hpp>

*// The string we are searching for*

**const** std::string search = "1kid";

*// Generate a random secret key. A random 32 bytes.*

bc::ec\_secret random\_secret(std::default\_random\_engine& engine);

*// Extract the Bitcoin address from an EC secret.*

std::string bitcoin\_address(**const** bc::ec\_secret& secret);

*// Case insensitive comparison with the search string.*

**bool** match\_found(**const** std::string& address);

**int** main()

{

std::random\_device random;

std::default\_random\_engine engine(random());

*// Loop continuously...*

Advanced Keys and Addresses | 101

**while** (true)

{

*// Generate a random secret.*

bc::ec\_secret secret = random\_secret(engine);

*// Get the address.*

std::string address = bitcoin\_address(secret);

*// Does it match our search string? (1kid)*

**if** (match\_found(address))

{

*// Success!*

std::cout << "Found vanity address! " << address << std::endl;

std::cout << "Secret: " << bc::encode\_hex(secret) << std::endl;

**return** 0;

}

}

*// Should never reach here!*

**return** 0;

}

bc::ec\_secret random\_secret(std::default\_random\_engine& engine)

{

*// Create new secret...*

bc::ec\_secret secret;

*// Iterate through every byte setting a random value...*

**for** (**uint8\_t**& byte: secret)

byte = engine() % std::numeric\_limits<**uint8\_t**>::max();

*// Return result.*

**return** secret;

}

std::string bitcoin\_address(**const** bc::ec\_secret& secret)

{

*// Convert secret to pubkey...*

bc::ec\_point pubkey = bc::secret\_to\_public\_key(secret);

*// Finally create address.*

bc::payment\_address payaddr;

bc::set\_public\_key(payaddr, pubkey);

*// Return encoded form.*

**return** payaddr.encoded();

}

**bool** match\_found(**const** std::string& address)

{

**auto** addr\_it = address.begin();

*// Loop through the search string comparing it to the lower case*

*// character of the supplied address.*

**for** (**auto** it = search.begin(); it != search.end(); ++it, ++addr\_it)

**if** (\*it != std::tolower(\*addr\_it))

**return** false;

*// Reached end of search string, so address matches.*

**return** true;

}

102 | Chapter 4: Keys, Addresses, Wallets

The example code must be compiled using a C compiler and linked against the

libbitcoin library (which must be first installed on that system). To run

the example, run the vanity-miner++ executable with no parameters (see

Example 4-9) and it will attempt to find a vanity address starting with “1kid”.

*Example 4-9. Compiling and running the vanity-miner example*

$ *# Compile the code with g++*

$ g++ -o vanity-miner vanity-miner.cpp **$(**pkg-config --cflags --libs libbitcoin**)**

$ *# Run the example*

$ ./vanity-miner

Found vanity address! 1KiDzkG4MxmovZryZRj8tK81oQRhbZ46YT

Secret: 57cc268a05f83a23ac9d930bc8565bac4e277055f4794cbd1a39e5e71c038f3f

$ *# Run it again for a different result*

$ ./vanity-miner

Found vanity address! 1Kidxr3wsmMzzouwXibKfwTYs5Pau8TUFn

Secret: 7f65bbbbe6d8caae74a0c6a0d2d7b5c6663d71b60337299a1a2cf34c04b2a623

*# Use "time" to see how long it takes to find a result*

$ time ./vanity-miner

Found vanity address! 1KidPWhKgGRQWD5PP5TAnGfDyfWp5yceXM

Secret: 2a802e7a53d8aa237cd059377b616d2bfcfa4b0140bc85fa008f2d3d4b225349

real 0m8.868s

user 0m8.828s

sys 0m0.035s

The example code will take a few seconds to find a match for the three-character pattern

“kid”, as we can see when we use the time Unix command to measure the execution

time. Change the search pattern in the source code and see how much longer it takes

for four- or five-character patterns!

Vanity address security

Vanity addresses can be used to enhance *and* to defeat security measures; they are truly

a double-edged sword. Used to improve security, a distinctive address makes it harder

for adversaries to substitute their own address and fool your customers into paying them

instead of you. Unfortunately, vanity addresses also make it possible for anyone to create

an address that *resembles* any random address, or even another vanity address, thereby

fooling your customers.

Eugenia could advertise a randomly generated address (e.g., 1J7mdg5rbQyUHE

NYdx39WVWK7fsLpEoXZy) to which people can send their donations. Or, she could generate

a vanity address that starts with 1Kids, to make it more distinctive.

In both cases, one of the risks of using a single fixed address (rather than a separate

dynamic address per donor) is that a thief might be able to infiltrate your website and

replace it with his own address, thereby diverting donations to himself. If you have

advertised your donation address in a number of different places, your users may vis‐

Advanced Keys and Addresses | 103

ually inspect the address before making a payment to ensure it is the same one they saw

on your website, on your email, and on your flyer. In the case of a random address like

1J7mdg5rbQyUHENYdx39WVWK7fsLpEoXZy, the average user will perhaps inspect the first

few characters “1J7mdg” and be satisfied that the address matches. Using a vanity address

generator, someone with the intent to steal by substituting a similar-looking address

can quickly generate addresses that match the first few characters, as shown in

Table 4-13.

*Table 4-13. Generating vanity addresses to match a random address*

**Original Random Address** 1J7mdg5rbQyUHENYdx39WVWK7fsLpEoXZy

**Vanity (4 character match)** 1J7md1QqU4LpctBetHS2ZoyLV5d6dShhEy

**Vanity (5 character match)** 1J7mdgYqyNd4ya3UEcq31Q7sqRMXw2XZ6n

**Vanity (6 character match)** 1J7mdg5WxGENmwyJP9xuGhG5KRzu99BBCX

So does a vanity address increase security? If Eugenia generates the vanity address

1Kids33q44erFfpeXrmDSz7zEqG2FesZEN, users are likely to look at the vanity pattern

word *and a few characters beyond*, for example noticing the “1Kids33” part of the address.

That would force an attacker to generate a vanity address matching at least six

characters (two more), expending an effort that is 3,364 times (58 × 58) higher than the

effort Eugenia expended for her four-character vanity. Essentially, the effort Eugenia

expends (or pays a vanity pool for) “pushes” the attacker into having to produce a longer

pattern vanity. If Eugenia pays a pool to generate an 8-character vanity address, the

attacker would be pushed into the realm of 10 characters, which is infeasible on a personal

computer and expensive even with a custom vanity-mining rig or vanity pool.

What is affordable for Eugenia becomes unaffordable for the attacker, especially if the

potential reward of fraud is not high enough to cover the cost of the vanity address

generation.

Paper Wallets

Paper wallets are bitcoin private keys printed on paper. Often the paper wallet also

includes the corresponding bitcoin address for convenience, but this is not necessary

because it can be derived from the private key. Paper wallets are a very effective way to

create backups or offline bitcoin storage, also known as “cold storage.” As a backup

mechanism, a paper wallet can provide security against the loss of key due to a computer

mishap such as a hard drive failure, theft, or accidental deletion. As a “cold storage”

mechanism, if the paper wallet keys are generated offline and never stored on a computer

system, they are much more secure against hackers, key-loggers, and other online computer

threats.

Paper wallets come in many shapes, sizes, and designs, but at a very basic level are just

a key and an address printed on paper. Table 4-14 shows the simplest form of a paper

wallet.

104 | Chapter 4: Keys, Addresses, Wallets

*Table 4-14. Simplest form of a paper wallet—a printout of the bitcoin address and private*

*key.*

Public Address Private Key (WIF)

1424C2F4bC9JidNjjTUZCbUxv6Sa1Mt62x 5J3mBbAH58CpQ3Y5RNJpUKPE62SQ5tfcvU2JpbnkeyhfsYB1Jcn

Paper wallets can be generated easily using a tool such as the client-side JavaScript

generator at *bitaddress.org*. This page contains all the code necessary to generate keys

and paper wallets, even while completely disconnected from the Internet. To use it, save

the HTML page on your local drive or on an external USB flash drive. Disconnect from

the Internet and open the file in a browser. Even better, boot your computer using a

pristine operating system, such as a CD-ROM bootable Linux OS. Any keys generated

with this tool while offline can be printed on a local printer over a USB cable (not

wirelessly), thereby creating paper wallets whose keys exist only on the paper and have

never been stored on any online system. Put these paper wallets in a fireproof safe and

“send” bitcoin to their bitcoin address, to implement a simple yet highly effective “cold

storage” solution. Figure 4-14 shows a paper wallet generated from the bitaddress.org

site.

*Figure 4-14. An example of a simple paper wallet from bitaddress.org*

The disadvantage of the simple paper wallet system is that the printed keys are vulnerable

to theft. A thief who is able to gain access to the paper can either steal it or photograph

the keys and take control of the bitcoins locked with those keys. A more sophisticated

paper wallet storage system uses BIP0038 encrypted private keys. The keys printed on

the paper wallet are protected by a passphrase that the owner has memorized. Without

the passphrase, the encrypted keys are useless. Yet, they still are superior to a passphraseprotected

wallet because the keys have never been online and must be physically retrieved

from a safe or other physically secured storage. Figure 4-15 shows a paper wallet

with an encrypted private key (BIP0038) created on the bitaddress.org site.

Advanced Keys and Addresses | 105

*Figure 4-15. An example of an encrypted paper wallet from bitaddress.org. The passphrase*

*is “test.”*

Although you can deposit funds into a paper wallet several times,

you should withdraw all funds only once, spending everything. This

is because in the process of unlocking and spending funds, you expose

the private key, and because some wallets might generate a

change address if you spend less than the whole amount. One way

to do this is to withdraw the entire balance stored in the paper wallet

and send any remaining funds to a new paper wallet.

Paper wallets come in many designs and sizes, with many different features. Some are

intended to be given as gifts and have seasonal themes, such as Christmas and New

Year’s themes. Others are designed for storage in a bank vault or safe with the private

key hidden in some way, either with opaque scratch-off stickers, or folded and sealed

with tamper-proof adhesive foil. Figures 4-16 through 4-18 show various examples of

paper wallets with security and backup features.

*Figure 4-16. An example of a paper wallet from bitcoinpaperwallet.com with the private*

*key on a folding flap.*

106 | Chapter 4: Keys, Addresses, Wallets

*Figure 4-17. The bitcoinpaperwallet.com paper wallet with the private key concealed.*

Other designs feature additional copies of the key and address, in the form of detachable

stubs similar to ticket stubs, allowing you to store multiple copies to protect against fire,

flood, or other natural disasters.

*Figure 4-18. An example of a paper wallet with additional copies of the keys on a backup*

*“stub.”*

Advanced Keys and Addresses | 107

CHAPTER 5

Transactions

Introduction

Transactions are the most important part of the bitcoin system. Everything else in bitcoin

is designed to ensure that transactions can be created, propagated on the network,

validated, and finally added to the global ledger of transactions (the blockchain). Transactions

are data structures that encode the transfer of value between participants in the

bitcoin system. Each transaction is a public entry in bitcoin’s blockchain, the global

double-entry bookkeeping ledger.

In this chapter we will examine all the various forms of transactions, what they contain,

how to create them, how they are verified, and how they become part of the permanent

record of all transactions.

Transaction Lifecycle

A transaction’s lifecycle starts with the transaction’s creation, also known as *origination*.

The transaction is then signed with one or more signatures indicating the authorization

to spend the funds referenced by the transaction. The transaction is then broadcast

on the bitcoin network, where each network node (participant) validates and propagates

the transaction until it reaches (almost) every node in the network. Finally, the

transaction is verified by a mining node and included in a block of transactions that is

recorded on the blockchain.

Once recorded on the blockchain and confirmed by sufficient subsequent blocks (confirmations),

the transaction is a permanent part of the bitcoin ledger and is accepted as

valid by all participants. The funds allocated to a new owner by the transaction can then

be spent in a new transaction, extending the chain of ownership and beginning the

lifecycle of a transaction again.

109

Creating Transactions

In some ways it helps to think of a transaction in the same way as a paper check. Like a

check, a transaction is an instrument that expresses the intent to transfer money and is

not visible to the financial system until it is submitted for execution. Like a check, the

originator of the transaction does not have to be the one signing the transaction.

Transactions can be created online or offline by anyone, even if the person creating the

transaction is not an authorized signer on the account. For example, an accounts payable

clerk might process payable checks for signature by the CEO. Similarly, an accounts

payable clerk can create bitcoin transactions and then have the CEO apply digital signatures

to make them valid. Whereas a check references a specific account as the source

of the funds, a bitcoin transaction references a specific previous transaction as its source,

rather than an account.

Once a transaction has been created, it is signed by the owner (or owners) of the source

funds. If it is properly formed and signed, the signed transaction is now valid and contains

all the information needed to execute the transfer of funds. Finally, the valid transaction

has to reach the bitcoin network so that it can be propagated until it reaches a

miner for inclusion in the pubic ledger (the blockchain).

Broadcasting Transactions to the Bitcoin Network

First, a transaction needs to be delivered to the bitcoin network so that it can be propagated

and included in the blockchain. In essence, a bitcoin transaction is just 300 to 400

bytes of data and has to reach any one of tens of thousands of bitcoin nodes. The senders

do not need to trust the nodes they use to broadcast the transaction, as long as they use

more than one to ensure that it propagates. The nodes don’t need to trust the sender or

establish the sender’s “identity.” Because the transaction is signed and contains no confidential

information, private keys, or credentials, it can be publicly broadcast using any

underlying network transport that is convenient. Unlike credit card transactions, for

example, which contain sensitive information and can only be transmitted on encrypted

networks, a bitcoin transaction can be sent over any network. As long as the transaction

can reach a bitcoin node that will propagate it into the bitcoin network, it doesn’t matter

how it is transported to the first node.

Bitcoin transactions can therefore be transmitted to the bitcoin network over insecure

networks such as WiFi, Bluetooth, NFC, Chirp, barcodes, or by copying and pasting

into a web form. In extreme cases, a bitcoin transaction could be transmitted over packet

radio, satellite relay, or shortwave using burst transmission, spread spectrum, or frequency

hopping to evade detection and jamming. A bitcoin transaction could even be

encoded as smileys (emoticons) and posted in a public forum or sent as a text message

or Skype chat message. Bitcoin has turned money into a data structure, making it virtually

impossible to stop anyone from creating and executing a bitcoin transaction.

110 | Chapter 5: Transactions

Propagating Transactions on the Bitcoin Network

Once a bitcoin transaction is sent to any node connected to the bitcoin network, the

transaction will be validated by that node. If valid, that node will propagate it to the

other nodes to which it is connected, and a success message will be returned synchronously

to the originator. If the transaction is invalid, the node will reject it and synchronously

return a rejection message to the originator.

The bitcoin network is a peer-to-peer network, meaning that each bitcoin node is connected

to a few other bitcoin nodes that it discovers during startup through the peerto-

peer protocol. The entire network forms a loosely connected mesh without a fixed

topology or any structure, making all nodes equal peers. Messages, including transactions

and blocks, are propagated from each node to the peers to which it is connected.

A new validated transaction injected into any node on the network will be sent to three

to four of the neighboring nodes, each of which will send it to three to four more nodes,

and so on. In this way, within a few seconds a valid transaction will propagate in an

exponentially expanding ripple across the network until all connected nodes have received

it.

The bitcoin network is designed to propagate transactions and blocks to all nodes in an

efficient and resilient manner that is resistant to attacks. To prevent spamming, denialof-

service attacks, or other nuisance attacks against the bitcoin system, every node independently

validates every transaction before propagating it further. A malformed

transaction will not get beyond one node. The rules by which transactions are validated

are explained in more detail in “Independent Verification of Transactions” on page 177.

Transaction Structure

A transaction is a *data structure* that encodes a transfer of value from a source of funds,

called an *input*, to a destination, called an *output*. Transaction inputs and outputs are

not related to accounts or identities. Instead, you should think of them as bitcoin

amounts—chunks of bitcoin—being locked with a specific secret that only the owner,

or person who knows the secret, can unlock. A transaction contains a number of fields,

as shown in Table 5-1.

*Table 5-1. The structure of a transaction*

Size Field Description

4 bytes Version Specifies which rules this transaction follows

1–9 bytes (VarInt) Input Counter How many inputs are included

Variable Inputs One or more transaction inputs

1–9 bytes (VarInt) Output Counter How many outputs are included

Variable Outputs One or more transaction outputs

4 bytes Locktime A Unix timestamp or block number

Transaction Structure | 111

Transaction Locktime

Locktime defines the earliest time that a transaction can be added to the blockchain. It

is set to zero in most transactions to indicate immediate execution. If locktime is nonzero

and below 500 million, it is interpreted as a block height, meaning the transaction is not

included in the blockchain prior to the specified block height. If it is above 500 million,

it is interpreted as a Unix Epoch timestamp (seconds since Jan-1-1970) and the transaction

is not included in the blockchain prior to the specified time. The use of locktime

is equivalent to postdating a paper check.

Transaction Outputs and Inputs

The fundamental building block of a bitcoin transaction is an *unspent transaction output*,

or UTXO. UTXO are indivisible chunks of bitcoin currency locked to a specific

owner, recorded on the blockchain, and recognized as currency units by the entire network.

The bitcoin network tracks all available (unspent) UTXO currently numbering

in the millions. Whenever a user receives bitcoin, that amount is recorded within the

blockchain as a UTXO. Thus, a user’s bitcoin might be scattered as UTXO amongst

hundreds of transactions and hundreds of blocks. In effect, there is no such thing as a

stored balance of a bitcoin address or account; there are only scattered UTXO, locked

to specific owners. The concept of a user’s bitcoin balance is a derived construct created

by the wallet application. The wallet calculates the user’s balance by scanning the blockchain

and aggregating all UTXO belonging to that user.

There are no accounts or balances in bitcoin; there are only *unspent*

*transaction outputs* (UTXO) scattered in the blockchain.

A UTXO can have an arbitrary value denominated as a multiple of satoshis. Just like

dollars can be divided down to two decimal places as cents, bitcoins can be divided

down to eight decimal places as satoshis. Although UTXO can be any arbitrary value,

once created it is indivisible just like a coin that cannot be cut in half. If a UTXO is larger

than the desired value of a transaction, it must still be consumed in its entirety and

change must be generated in the transaction. In other words, if you have a 20 bitcoin

UTXO and want to pay 1 bitcoin, your transaction must consume the entire 20 bitcoin

UTXO and produce two outputs: one paying 1 bitcoin to your desired recipient and

another paying 19 bitcoin in change back to your wallet. As a result, most bitcoin transactions

will generate change.

112 | Chapter 5: Transactions

Imagine a shopper buying a $1.50 beverage, reaching into her wallet and trying to find

a combination of coins and bank notes to cover the $1.50 cost. The shopper will choose

exact change if available (a dollar bill and two quarters), or a combination of smaller

denominations (six quarters), or if necessary, a larger unit such as a five dollar bank

note. If she hands too much money, say $5, to the shop owner, she will expect $3.50

change, which she will return to her wallet and have available for future transactions.

Similarly, a bitcoin transaction must be created from a user’s UTXO in whatever denominations

that user has available. Users cannot cut a UTXO in half any more than

they can cut a dollar bill in half and use it as currency. The user’s wallet application will

typically select from the user’s available UTXO various units to compose an amount

greater than or equal to the desired transaction amount.

As with real life, the bitcoin application can use several strategies to satisfy the purchase

amount: combining several smaller units, finding exact change, or using a single unit

larger than the transaction value and making change. All of this complex assembly of

spendable UTXO is done by the user’s wallet automatically and is invisible to users. It

is only relevant if you are programmatically constructing raw transactions from UTXO.

The UTXO consumed by a transaction are called transaction inputs, and the UTXO

created by a transaction are called transaction outputs. This way, chunks of bitcoin value

move forward from owner to owner in a chain of transactions consuming and creating

UTXO. Transactions consume UTXO by unlocking it with the signature of the current

owner and create UTXO by locking it to the bitcoin address of the new owner.

The exception to the output and input chain is a special type of transaction called the

*coinbase* transaction, which is the first transaction in each block. This transaction is

placed there by the “winning” miner and creates brand-new bitcoin payable to that

miner as a reward for mining. This is how bitcoin’s money supply is created during the

mining process, as we will see in Chapter 8.

What comes first? Inputs or outputs, the chicken or the egg? Strictly

speaking, outputs come first because coinbase transactions, which

generate new bitcoin, have no inputs and create outputs from nothing.

Transaction Outputs

Every bitcoin transaction creates outputs, which are recorded on the bitcoin ledger.

Almost all of these outputs, with one exception (see “Data Output (OP\_RETURN)” on

page 130) create spendable chunks of bitcoin called *unspent transaction outputs* or UTXO,

which are then recognized by the whole network and available for the owner to spend

in a future transaction. Sending someone bitcoin is creating an unspent transaction

output (UTXO) registered to their address and available for them to spend.

Transaction Outputs and Inputs | 113

UTXO are tracked by every full-node bitcoin client in a database held in memory, called

the *UTXO set* or *UTXO pool*. New transactions consume (spend) one or more of these

outputs from the UTXO set.

Transaction outputs consist of two parts:

• An amount of bitcoin, denominated in *satoshis*, the smallest bitcoin unit

• A *locking script*, also known as an “encumbrance” that “locks” this amount by specifying

the conditions that must be met to spend the output

The transaction scripting language, used in the locking script mentioned previously, is

discussed in detail in “Transaction Scripts and Script Language” on page 121. Table 5-2

shows the structure of a transaction output.

*Table 5-2. The structure of a transaction output*

Size Field Description

8 bytes Amount Bitcoin value in satoshis (10-8 bitcoin)

1-9 bytes (VarInt) Locking-Script Size Locking-Script length in bytes, to follow

Variable Locking-Script A script defining the conditions needed to spend the output

In Example 5-1, we use the blockchain.info API to find the unspent outputs (UTXO)

of a specific address.

*Example 5-1. A script that calls the blockchain.info API to find the UTXO related to an*

*address*

*# get unspent outputs from blockchain API*

**import json**

**import requests**

*# example address*

address = '1Dorian4RoXcnBv9hnQ4Y2C1an6NJ4UrjX'

*# The API URL is https://blockchain.info/unspent?active=<address>*

*# It returns a JSON object with a list "unspent\_outputs", containing UTXO, like*

*this:*

*#{ "unspent\_outputs":[*

*# {*

*# "tx\_hash":"ebadfaa92f1fd29e2fe296eda702c48bd11ffd52313e986e99ddad9084062167",*

*# "tx\_index":51919767,*

*# "tx\_output\_n": 1,*

*# "script":"76a9148c7e252f8d64b0b6e313985915110fcfefcf4a2d88ac",*

*# "value": 8000000,*

*# "value\_hex": "7a1200",*

*# "confirmations":28691*

*# },*

*# ...*

114 | Chapter 5: Transactions

*#]}*

resp = requests.get('https://blockchain.info/unspent?active=%s' % address)

utxo\_set = json.loads(resp.text)["unspent\_outputs"]

**for** utxo **in** utxo\_set:

**print** "%s:%d - %ld Satoshis" % (utxo['tx\_hash'], utxo['tx\_output\_n'], utxo['val

ue'])

Running the script, we see a list of transaction IDs, a colon, the index number of the

specific unspent transaction output (UTXO), and the value of that UTXO in satoshis.

The locking script is not shown in the output in Example 5-2.

*Example 5-2. Running the get-utxo.py script*

$ python get-utxo.py

ebadfaa92f1fd29e2fe296eda702c48bd11ffd52313e986e99ddad9084062167:1 - 8000000 Satoshis

6596fd070679de96e405d52b51b8e1d644029108ec4cbfe451454486796a1ecf:0 - 16050000 Satoshis

74d788804e2aae10891d72753d1520da1206e6f4f20481cc1555b7f2cb44aca0:0 - 5000000 Satoshis

b2affea89ff82557c60d635a2a3137b8f88f12ecec85082f7d0a1f82ee203ac4:0 - 10000000 Satoshis

...

Spending conditions (encumbrances)

Transaction outputs associate a specific amount (in satoshis) to a specific *encumbrance*

or locking script that defines the condition that must be met to spend that

amount. In most cases, the locking script will lock the output to a specific bitcoin address,

thereby transferring ownership of that amount to the new owner. When Alice

paid Bob’s Cafe for a cup of coffee, her transaction created a 0.015 bitcoin output *encumbered*

or locked to the cafe’s bitcoin address. That 0.015 bitcoin output was recorded

on the blockchain and became part of the Unspent Transaction Output set, meaning it

showed in Bob’s wallet as part of the available balance. When Bob chooses to spend that

amount, his transaction will release the encumbrance, unlocking the output by providing

an unlocking script containing a signature from Bob’s private key.

Transaction Inputs

In simple terms, transaction inputs are pointers to UTXO. They point to a specific

UTXO by reference to the transaction hash and sequence number where the UTXO is

recorded in the blockchain. To spend UTXO, a transaction input also includes unlocking

scripts that satisfy the spending conditions set by the UTXO. The unlocking script is

usually a signature proving ownership of the bitcoin address that is in the locking script.

Transaction Outputs and Inputs | 115

When users make a payment, their wallet constructs a transaction by selecting from the

available UTXO. For example, to make a 0.015 bitcoin payment, the wallet app may

select a 0.01 UTXO and a 0.005 UTXO, using them both to add up to the desired payment

amount.

In Example 5-3, we show the use of a “greedy” algorithm to select from available UTXO

in order to make a specific payment amount. In the example, the available UTXO are

provided as a constant array, but in reality, the available UTXO would be retrieved with

an RPC call to Bitcoin Core, or to a third-party API as shown in Example 5-1.

*Example 5-3. A script for calculating how much total bitcoin will be issued*

*# Selects outputs from a UTXO list using a greedy algorithm.*

**from sys import** argv

**class OutputInfo**:

**def** \_\_init\_\_(self, tx\_hash, tx\_index, value):

self.tx\_hash = tx\_hash

self.tx\_index = tx\_index

self.value = value

**def** \_\_repr\_\_(self):

**return** "<%s:%s with %s Satoshis>" % (self.tx\_hash, self.tx\_index,

self.value)

*# Select optimal outputs for a send from unspent outputs list.*

*# Returns output list and remaining change to be sent to*

*# a change address.*

**def** select\_outputs\_greedy(unspent, min\_value):

*# Fail if empty.*

**if not** unspent:

**return** None

*# Partition into 2 lists.*

lessers = [utxo **for** utxo **in** unspent **if** utxo.value < min\_value]

greaters = [utxo **for** utxo **in** unspent **if** utxo.value >= min\_value]

key\_func = **lambda** utxo: utxo.value

**if** greaters:

*# Not-empty. Find the smallest greater.*

min\_greater = min(greaters)

change = min\_greater.value - min\_value

**return** [min\_greater], change

*# Not found in greaters. Try several lessers instead.*

*# Rearrange them from biggest to smallest. We want to use the least*

*# amount of inputs as possible.*

lessers.sort(key=key\_func, reverse=True)

result = []

accum = 0

**for** utxo **in** lessers:

result.append(utxo)

116 | Chapter 5: Transactions

accum += utxo.value

**if** accum >= min\_value:

change = accum - min\_value

**return** result, "Change: %d Satoshis" % change

*# No results found.*

**return** None, 0

**def** main():

unspent = [

OutputInfo("ebad

faa92f1fd29e2fe296eda702c48bd11ffd52313e986e99ddad9084062167", 1, 8000000),

OutputIn

fo("6596fd070679de96e405d52b51b8e1d644029108ec4cbfe451454486796a1ecf", 0,

16050000),

OutputInfo("b2af

fea89ff82557c60d635a2a3137b8f88f12ecec85082f7d0a1f82ee203ac4", 0, 10000000),

OutputIn

fo("7dbc497969c7475e45d952c4a872e213fb15d45e5cd3473c386a71a1b0c136a1", 0,

25000000),

OutputIn

fo("55ea01bd7e9afd3d3ab9790199e777d62a0709cf0725e80a7350fdb22d7b8ec6", 17,

5470541),

OutputIn

fo("12b6a7934c1df821945ee9ee3b3326d07ca7a65fd6416ea44ce8c3db0c078c64", 0,

10000000),

OutputIn

fo("7f42eda67921ee92eae5f79bd37c68c9cb859b899ce70dba68c48338857b7818", 0,

16100000),

]

**if** len(argv) > 1:

target = long(argv[1])

**else**:

target = 55000000

**print** "For transaction amount %d Satoshis (%f bitcoin) use: " % (target, target/

10.0\*\*8)

**print** select\_outputs\_greedy(unspent, target)

**if** \_\_name\_\_ == "\_\_main\_\_":

main()

If we run the *select-utxo.py* script without a parameter, it will attempt to construct a set

of UTXO (and change) for a payment of 55,000,000 satoshis (0.55 bitcoin). If you provide

a target payment amount as a parameter, the script will select UTXO to make that

target payment amount. In Example 5-4, we run the script trying to make a payment of

0.5 bitcoin or 50,000,000 satoshis.

*Example 5-4. Running the select-utxo.py script*

$ python select-utxo.py 50000000

For transaction amount 50000000 Satoshis (0.500000 bitcoin) use:

Transaction Outputs and Inputs | 117

([<7dbc497969c7475e45d952c4a872e213fb15d45e5cd3473c386a71a1b0c136a1:0 with 25000000

Satoshis>, <7f42eda67921ee92eae5f79bd37c68c9cb859b899ce70dba68c48338857b7818:0 with

16100000 Satoshis>,

<6596fd070679de96e405d52b51b8e1d644029108ec4cbfe451454486796a1ecf:0 with 16050000

Satoshis>], 'Change: 7150000 Satoshis')

Once the UTXO is selected, the wallet then produces unlocking scripts containing signatures

for each of the UTXO, thereby making them spendable by satisfying their locking

script conditions. The wallet adds these UTXO references and unlocking scripts as

inputs to the transaction. Table 5-3 shows the structure of a transaction input.

*Table 5-3. The structure of a transaction input*

Size Field Description

32 bytes Transaction Hash Pointer to the transaction containing the UTXO to be spent

4 bytes Output Index The index number of the UTXO to be spent; first one is 0

1-9 bytes (VarInt) Unlocking-Script Size Unlocking-Script length in bytes, to follow

Variable Unlocking-Script A script that fulfills the conditions of the UTXO locking script.

4 bytes Sequence Number Currently disabled Tx-replacement feature, set to 0xFFFFFFFF

The sequence number is used to override a transaction prior to the

expiration of the transaction locktime, which is a feature that is currently

disabled in bitcoin. Most transactions set this value to the

maximum integer value (0xFFFFFFFF) and it is ignored by the bitcoin

network. If the transaction has a nonzero locktime, at least one

of its inputs must have a sequence number below 0xFFFFFFFF in

order to enable locktime.

Transaction Fees

Most transactions include transaction fees, which compensate the bitcoin miners for

securing the network. Mining and the fees and rewards collected by miners are discussed

in more detail in Chapter 8. This section examines how transaction fees are included

in a typical transaction. Most wallets calculate and include transaction fees automatically.

However, if you are constructing transactions programmatically, or using a

command-line interface, you must manually account for and include these fees.

Transaction fees serve as an incentive to include (mine) a transaction into the next block

and also as a disincentive against “spam” transactions or any kind of abuse of the system,

by imposing a small cost on every transaction. Transaction fees are collected by the

miner who mines the block that records the transaction on the blockchain.

Transaction fees are calculated based on the size of the transaction in kilobytes, not the

value of the transaction in bitcoin. Overall, transaction fees are set based on market

forces within the bitcoin network. Miners prioritize transactions based on many dif‐

118 | Chapter 5: Transactions

ferent criteria, including fees, and might even process transactions for free under certain

circumstances. Transaction fees affect the processing priority, meaning that a transaction

with sufficient fees is likely to be included in the next-most–mined block, whereas

a transaction with insufficient or no fees might be delayed, processed on a best-effort

basis after a few blocks, or not processed at all. Transaction fees are not mandatory, and

transactions without fees might be processed eventually; however, including transaction

fees encourages priority processing.

Over time, the way transaction fees are calculated and the effect they have on transaction

prioritization has been evolving. At first, transaction fees were fixed and constant across

the network. Gradually, the fee structure has been relaxed so that it may be influenced

by market forces, based on network capacity and transaction volume. The current minimum

transaction fee is fixed at 0.0001 bitcoin or a tenth of a milli-bitcoin per kilobyte,

recently decreased from one milli-bitcoin. Most transactions are less than one kilobyte;

however, those with multiple inputs or outputs can be larger. In future revisions of the

bitcoin protocol, it is expected that wallet applications will use statistical analysis to

calculate the most appropriate fee to attach to a transaction based on the average fees

of recent transactions.

The current algorithm used by miners to prioritize transactions for inclusion in a block

based on their fees is examined in detail in Chapter 8.

Adding Fees to Transactions

The data structure of transactions does not have a field for fees. Instead, fees are implied

as the difference between the sum of inputs and the sum of outputs. Any excess amount

that remains after all outputs have been deducted from all inputs is the fee that is collected

by the miners.

Transaction fees are implied, as the excess of inputs minus outputs:

Fees = Sum(Inputs) – Sum(Outputs)

This is a somewhat confusing element of transactions and an important point to understand,

because if you are constructing your own transactions you must ensure you

do not inadvertently include a very large fee by underspending the inputs. That means

that you must account for all inputs, if necessary by creating change, or you will end up

giving the miners a very big tip!

For example, if you consume a 20-bitcoin UTXO to make a 1-bitcoin payment, you

must include a 19-bitcoin change output back to your wallet. Otherwise, the 19-bitcoin

“leftover” will be counted as a transaction fee and will be collected by the miner who

mines your transaction in a block. Although you will receive priority processing and

make a miner very happy, this is probably not what you intended.

Transaction Outputs and Inputs | 119

If you forget to add a change output in a manually constructed

transaction, you will be paying the change as a transaction fee. “Keep

the change!” might not be what you intended.

Let’s see how this works in practice, by looking at Alice’s coffee purchase again. Alice

wants to spend 0.015 bitcoin to pay for coffee. To ensure this transaction is processed

promptly, she will want to include a transaction fee, say 0.001. That will mean that the

total cost of the transaction will be 0.016. Her wallet must therefore source a set of UTXO

that adds up to 0.016 bitcoin or more and, if necessary, create change. Let’s say her wallet

has a 0.2-bitcoin UTXO available. It will therefore need to consume this UTXO, create

one output to Bob’s Cafe for 0.015, and a second output with 0.184 bitcoin in change

back to her own wallet, leaving 0.001 bitcoin unallocated, as an implicit fee for the

transaction.

Now let’s look at a different scenario. Eugenia, our children’s charity director in the

Philippines, has completed a fundraiser to purchase school books for the children. She

received several thousand small donations from people all around the world, totaling

50 bitcoin, so her wallet is full of very small payments (UTXO). Now she wants to

purchase hundreds of school books from a local publisher, paying in bitcoin.

As Eugenia’s wallet application tries to construct a single larger payment transaction, it

must source from the available UTXO set, which is composed of many smaller amounts.

That means that the resulting transaction will source from more than a hundred smallvalue

UTXO as inputs and only one output, paying the book publisher. A transaction

with that many inputs will be larger than one kilobyte, perhaps 2 to 3 kilobytes in size.

As a result, it will require a higher fee than the minimal network fee of 0.0001 bitcoin.

Eugenia’s wallet application will calculate the appropriate fee by measuring the size of

the transaction and multiplying that by the per-kilobyte fee. Many wallets will overpay

fees for larger transactions to ensure the transaction is processed promptly. The higher

fee is not because Eugenia is spending more money, but because her transaction is more

complex and larger in size—the fee is independent of the transaction’s bitcoin value.

Transaction Chaining and Orphan Transactions

As we have seen, transactions form a chain, whereby one transaction spends the outputs

of the previous transaction (known as the parent) and creates outputs for a subsequent

transaction (known as the child). Sometimes an entire chain of transactions depending

on each other—say a parent, child, and grandchild transaction—are created at the same

time, to fulfill a complex transactional workflow that requires valid children to be signed

before the parent is signed. For example, this is a technique used in CoinJoin transactions

where multiple parties join transactions together to protect their privacy.

120 | Chapter 5: Transactions

When a chain of transactions is transmitted across the network, they don’t always arrive

in the same order. Sometimes, the child might arrive before the parent. In that case, the

nodes that see a child first can see that it references a parent transaction that is not yet

known. Rather than reject the child, they put it in a temporary pool to await the arrival

of its parent and propagate it to every other node. The pool of transactions without

parents is known as the *orphan transaction pool*. Once the parent arrives, any orphans

that reference the UTXO created by the parent are released from the pool, revalidated

recursively, and then the entire chain of transactions can be included in the transaction

pool, ready to be mined in a block. Transaction chains can be arbitrarily long, with any

number of generations transmitted simultaneously. The mechanism of holding orphans

in the orphan pool ensures that otherwise valid transactions will not be rejected just

because their parent has been delayed and that eventually the chain they belong to is

reconstructed in the correct order, regardless of the order of arrival.

There is a limit to the number of orphan transactions stored in memory, to prevent a

denial-of-service attack against bitcoin nodes. The limit is defined as MAX\_ORPHAN\_TRANS

ACTIONS in the source code of the bitcoin reference client. If the number of orphan

transactions in the pool exceeds MAX\_ORPHAN\_TRANSACTIONS, one or more randomly

selected orphan transactions are evicted from the pool, until the pool size is back within

limits.

Transaction Scripts and Script Language

Bitcoin clients validate transactions by executing a script, written in a Forth-like scripting

language. Both the locking script (encumbrance) placed on a UTXO and the unlocking

script that usually contains a signature are written in this scripting language.

When a transaction is validated, the unlocking script in each input is executed alongside

the corresponding locking script to see if it satisfies the spending condition.

Today, most transactions processed through the bitcoin network have the form “Alice

pays Bob” and are based on the same script called a Pay-to-Public-Key-Hash script.

However, the use of scripts to lock outputs and unlock inputs means that through use

of the programming language, transactions can contain an infinite number of conditions.

Bitcoin transactions are not limited to the “Alice pays Bob” form and pattern.

This is only the tip of the iceberg of possibilities that can be expressed with this scripting

language. In this section, we will demonstrate the components of the bitcoin transaction

scripting language and show how it can be used to express complex conditions for

spending and how those conditions can be satisfied by unlocking scripts.

Transaction Scripts and Script Language | 121

Bitcoin transaction validation is not based on a static pattern, but

instead is achieved through the execution of a scripting language. This

language allows for a nearly infinite variety of conditions to be expressed.

This is how bitcoin gets the power of “programmable money.”

Script Construction (Lock + Unlock)

Bitcoin’s transaction validation engine relies on two types of scripts to validate transactions:

a locking script and an unlocking script.

A locking script is an encumbrance placed on an output, and it specifies the conditions

that must be met to spend the output in the future. Historically, the locking script was

called a *scriptPubKey*, because it usually contained a public key or bitcoin address. In

this book we refer to it as a “locking script” to acknowledge the much broader range of

possibilities of this scripting technology. In most bitcoin applications, what we refer to

as a locking script will appear in the source code as scriptPubKey.

An unlocking script is a script that “solves,” or satisfies, the conditions placed on an

output by a locking script and allows the output to be spent. Unlocking scripts are part

of every transaction input, and most of the time they contain a digital signature produced

by the user’s wallet from his or her private key. Historically, the unlocking script

is called *scriptSig*, because it usually contained a digital signature. In most bitcoin applications,

the source code refers to the unlocking script as scriptSig. In this book, we

refer to it as an “unlocking script” to acknowledge the much broader range of locking

script requirements, because not all unlocking scripts must contain signatures.

Every bitcoin client will validate transactions by executing the locking and unlocking

scripts together. For each input in the transaction, the validation software will first retrieve

the UTXO referenced by the input. That UTXO contains a locking script defining

the conditions required to spend it. The validation software will then take the unlocking

script contained in the input that is attempting to spend this UTXO and execute the two

scripts.

In the original bitcoin client, the unlocking and locking scripts were concatenated and

executed in sequence. For security reasons, this was changed in 2010, because of a vulnerability

that allowed a malformed unlocking script to push data onto the stack and

corrupt the locking script. In the current implementation, the scripts are executed separately

with the stack transferred between the two executions, as described next.

First, the unlocking script is executed, using the stack execution engine. If the unlocking

script executed without errors (e.g., it has no “dangling” operators left over), the main

stack (not the alternate stack) is copied and the locking script is executed. If the result

of executing the locking script with the stack data copied from the unlocking script is

“TRUE,” the unlocking script has succeeded in resolving the conditions imposed by the

122 | Chapter 5: Transactions

locking script and, therefore, the input is a valid authorization to spend the UTXO. If

any result other than “TRUE” remains after execution of the combined script, the input

is invalid because it has failed to satisfy the spending conditions placed on the UTXO.

Note that the UTXO is permanently recorded in the blockchain, and therefore is invariable

and is unaffected by failed attempts to spend it by reference in a new transaction.

Only a valid transaction that correctly satisfies the conditions of the UTXO results in

the UTXO being marked as “spent” and removed from the set of available (unspent)

UTXO.

Figure 5-1 is an example of the unlocking and locking scripts for the most common

type of bitcoin transaction (a payment to a public key hash), showing the combined

script resulting from the concatenation of the unlocking and locking scripts prior to

script validation.

*Figure 5-1. Combining scriptSig and scriptPubKey to evaluate a transaction script*

Scripting Language

The bitcoin transaction script language, called *Script*, is a Forth-like reverse-polish notation

stack-based execution language. If that sounds like gibberish, you probably haven’t

studied 1960’s programming languages. Script is a very simple language that was

designed to be limited in scope and executable on a range of hardware, perhaps as simple

as an embedded device, such as a handheld calculator. It requires minimal processing

and cannot do many of the fancy things modern programming languages can do. In the

case of programmable money, that is a deliberate security feature.

Bitcoin’s scripting language is called a stack-based language because it uses a data structure

called a *stack*. A stack is a very simple data structure, which can be visualized as a

stack of cards. A stack allows two operations: push and pop. Push adds an item on top

of the stack. Pop removes the top item from the stack.

The scripting language executes the script by processing each item from left to right.

Numbers (data constants) are pushed onto the stack. Operators push or pop one or

more parameters from the stack, act on them, and might push a result onto the stack.

Transaction Scripts and Script Language | 123

For example, OP\_ADD will pop two items from the stack, add them, and push the resulting

sum onto the stack.

Conditional operators evaluate a condition, producing a boolean result of TRUE or

FALSE. For example, OP\_EQUAL pops two items from the stack and pushes TRUE (TRUE

is represented by the number 1) if they are equal or FALSE (represented by zero) if they

are not equal. Bitcoin transaction scripts usually contain a conditional operator, so that

they can produce the TRUE result that signifies a valid transaction.

In Figure 5-2, the script 2 3 OP\_ADD 5 OP\_EQUAL demonstrates the arithmetic addition

operator OP\_ADD, adding two numbers and putting the result on the stack, followed by

the conditional operator OP\_EQUAL, which checks that the resulting sum is equal to 5.

For brevity, the OP\_ prefix is omitted in the step-by-step example.

The following is a slightly more complex script, which calculates 2 + 7 – 3 + 1. Notice

that when the script contains several operators in a row, the stack allows the results of

one operator to be acted upon by the next operator:

2 7 OP\_ADD 3 OP\_SUB 1 OP\_ADD 7 OP\_EQUAL

Try validating the preceding script yourself using pencil and paper. When the script

execution ends, you should be left with the value TRUE on the stack.

Although most locking scripts refer to a bitcoin address or public key, thereby requiring

proof of ownership to spend the funds, the script does not have to be that complex. Any

combination of locking and unlocking scripts that results in a TRUE value is valid. The

simple arithmetic we used as an example of the scripting language is also a valid locking

script that can be used to lock a transaction output.

Use part of the arithmetic example script as the locking script:

3 OP\_ADD 5 OP\_EQUAL

which can be satisfied by a transaction containing an input with the unlocking script:

2

The validation software combines the locking and unlocking scripts and the resulting

script is:

2 3 OP\_ADD 5 OP\_EQUAL

As we saw in the step-by-step example in Figure 5-2, when this script is executed, the

result is OP\_TRUE, making the transaction valid. Not only is this a valid transaction output

locking script, but the resulting UTXO could be spent by anyone with the arithmetic

skills to know that the number 2 satisfies the script.

124 | Chapter 5: Transactions

*Figure 5-2. Bitcoin’s script validation doing simple math*

Transaction Scripts and Script Language | 125

Transactions are valid if the top result on the stack is TRUE (noted

as {0x01}), any other non-zero value or if the stack is empty after

script execution. Transactions are invalid if the top value on the stack

is FALSE (a zero-length empty value, noted as {}) or if script execution

is halted explicitly by an operator, such as OP\_VERIFY, OP\_RETURN,

or a conditional terminator such as OP\_ENDIF. See Appendix

A for details.

Turing Incompleteness

The bitcoin transaction script language contains many operators, but is deliberately

limited in one important way—there are no loops or complex flow control capabilities

other than conditional flow control. This ensures that the language is not *Turing Complete*,

meaning that scripts have limited complexity and predictable execution times.

Script is not a general-purpose language. These limitations ensure that the language

cannot be used to create an infinite loop or other form of “logic bomb” that could be

embedded in a transaction in a way that causes a denial-of-service attack against the

bitcoin network. Remember, every transaction is validated by every full node on the

bitcoin network. A limited language prevents the transaction validation mechanism

from being used as a vulnerability.

Stateless Verification

The bitcoin transaction script language is stateless, in that there is no state prior to

execution of the script, or state saved after execution of the script. Therefore, all the

information needed to execute a script is contained within the script. A script will predictably

execute the same way on any system. If your system verifies a script, you can

be sure that every other system in the bitcoin network will also verify the script, meaning

that a valid transaction is valid for everyone and everyone knows this. This predictability

of outcomes is an essential benefit of the bitcoin system.

Standard Transactions

In the first few years of bitcoin’s development, the developers introduced some limitations

in the types of scripts that could be processed by the reference client. These limitations

are encoded in a function called isStandard(), which defines five types of

“standard” transactions. These limitations are temporary and might be lifted by the time

you read this. Until then, the five standard types of transaction scripts are the only ones

that will be accepted by the reference client and most miners who run the reference

client. Although it is possible to create a nonstandard transaction containing a script

that is not one of the standard types, you must find a miner who does not follow these

limitations to mine that transaction into a block.

126 | Chapter 5: Transactions

Check the source code of the Bitcoin Core client (the reference implementation) to see

what is currently allowed as a valid transaction script.

The five standard types of transaction scripts are pay-to-public-key-hash (P2PKH),

public-key, multi-signature (limited to 15 keys), pay-to-script-hash (P2SH), and data

output (OP\_RETURN), which are described in more detail in the following sections.

Pay-to-Public-Key-Hash (P2PKH)

The vast majority of transactions processed on the bitcoin network are P2PKH transactions.

These contain a locking script that encumbers the output with a public key

hash, more commonly known as a bitcoin address. Transactions that pay a bitcoin address

contain P2PKH scripts. An output locked by a P2PKH script can be unlocked

(spent) by presenting a public key and a digital signature created by the corresponding

private key.

For example, let’s look at Alice’s payment to Bob’s Cafe again. Alice made a payment of

0.015 bitcoin to the cafe’s bitcoin address. That transaction output would have a locking

script of the form:

OP\_DUP OP\_HASH160 <Cafe Public Key Hash> OP\_EQUAL OP\_CHECKSIG

The Cafe Public Key Hash is equivalent to the bitcoin address of the cafe, without the

Base58Check encoding. Most applications would show the *public key hash* in hexadecimal

encoding and not the familiar bitcoin address Base58Check format that begins

with a “1”.

The preceding locking script can be satisfied with an unlocking script of the form:

<Cafe Signature> <Cafe Public Key>

The two scripts together would form the following combined validation script:

<Cafe Signature> <Cafe Public Key> OP\_DUP OP\_HASH160

<Cafe Public Key Hash> OP\_EQUAL OP\_CHECKSIG

When executed, this combined script will evaluate to TRUE if, and only if, the unlocking

script matches the conditions set by the locking script. In other words, the result will

be TRUE if the unlocking script has a valid signature from the cafe’s private key that

corresponds to the public key hash set as an encumbrance.

Figures 5-3 and 5-4 show (in two parts) a step-by-step execution of the combined script,

which will prove this is a valid transaction.

Standard Transactions | 127

*Figure 5-3. Evaluating a script for a P2PKH transaction (Part 1 of 2)*

Pay-to-Public-Key

Pay-to-public-key is a simpler form of a bitcoin payment than pay-to-public-key-hash.

With this script form, the public key itself is stored in the locking script, rather than a

public-key-hash as with P2PKH earlier, which is much shorter. Pay-to-public-key-hash

was invented by Satoshi to make bitcoin addresses shorter, for ease of use. Pay-to-publickey

is now most often seen in coinbase transactions, generated by older mining software

that has not been updated to use P2PKH.

A pay-to-public-key locking script looks like this:

<Public Key A> OP\_CHECKSIG

The corresponding unlocking script that must be presented to unlock this type of output

is a simple signature, like this:

<Signature from Private Key A>

The combined script, which is validated by the transaction validation software, is:

<Signature from Private Key A> <Public Key A> OP\_CHECKSIG

128 | Chapter 5: Transactions

This script is a simple invocation of the CHECKSIG operator, which validates the signature

as belonging to the correct key and returns TRUE on the stack.

*Figure 5-4. Evaluating a script for a P2PKH transaction (Part 2 of 2)*

Multi-Signature

Multi-signature scripts set a condition where N public keys are recorded in the script

and at least M of those must provide signatures to release the encumbrance. This is also

known as an M-of-N scheme, where N is the total number of keys and M is the threshold

of signatures required for validation. For example, a 2-of-3 multi-signature is one where

three public keys are listed as potential signers and at least two of those must be used to

Standard Transactions | 129

create signatures for a valid transaction to spend the funds. At this time, standard multisignature

scripts are limited to at most 15 listed public keys, meaning you can do anything

from a 1-of-1 to a 15-of-15 multi-signature or any combination within that range.

The limitation to 15 listed keys might be lifted by the time this book is published, so

check the isStandard() function to see what is currently accepted by the network.

The general form of a locking script setting an M-of-N multi-signature condition is:

M <Public Key 1> <Public Key 2> ... <Public Key N> N OP\_CHECKMULTISIG

where N is the total number of listed public keys and M is the threshold of required

signatures to spend the output.

A locking script setting a 2-of-3 multi-signature condition looks like this:

2 <Public Key A> <Public Key B> <Public Key C> 3 OP\_CHECKMULTISIG

The preceding locking script can be satisfied with an unlocking script containing pairs

of signatures and public keys:

OP\_0 <Signature B> <Signature C>

or any combination of two signatures from the private keys corresponding to the three

listed public keys.

The prefix OP\_0 is required because of a bug in the original implementation

of CHECKMULTISIG where one item too many is popped off

the stack. It is ignored by CHECKMULTISIG and is simply a placeholder.

The two scripts together would form the combined validation script:

OP\_0 <Signature B> <Signature C> 2 <Public Key A> <Public Key B> <Public Key C>

3 OP\_CHECKMULTISIG

When executed, this combined script will evaluate to TRUE if, and only if, the unlocking

script matches the conditions set by the locking script. In this case, the condition is

whether the unlocking script has a valid signature from the two private keys that correspond

to two of the three public keys set as an encumbrance.

Data Output (OP\_RETURN)

Bitcoin’s distributed and timestamped ledger, the blockchain, has potential uses far beyond

payments. Many developers have tried to use the transaction scripting language

to take advantage of the security and resilience of the system for applications such as

digital notary services, stock certificates, and smart contracts. Early attempts to use

bitcoin’s script language for these purposes involved creating transaction outputs that

recorded data on the blockchain; for example, to record a digital fingerprint of a file in

130 | Chapter 5: Transactions

such a way that anyone could establish proof-of-existence of that file on a specific date

by reference to that transaction.

The use of bitcoin’s blockchain to store data unrelated to bitcoin payments is a controversial

subject. Many developers consider such use abusive and want to discourage it.

Others view it as a demonstration of the powerful capabilities of blockchain technology

and want to encourage such experimentation. Those who object to the inclusion of nonpayment

data argue that it causes “blockchain bloat,” burdening those running full bitcoin

nodes with carrying the cost of disk storage for data that the blockchain was not

intended to carry. Moreover, such transactions create UTXO that cannot be spent, using

the destination bitcoin address as a free-form 20-byte field. Because the address is used

for data, it doesn’t correspond to a private key and the resulting UTXO can *never* be

spent; it’s a fake payment. This practice causes the size of the in-memory UTXO set to

increase and these transactions that can never be spent are therefore never removed,

forcing bitcoin nodes to carry these forever in RAM, which is far more expensive.

In version 0.9 of the Bitcoin Core client, a compromise was reached with the introduction

of the OP\_RETURN operator. OP\_RETURN allows developers to add 40 bytes of nonpayment

data to a transaction output. However, unlike the use of “fake” UTXO, the

OP\_RETURN operator creates an explicitly *provably unspendable* output, which does not

need to be stored in the UTXO set. OP\_RETURN outputs are recorded on the blockchain,

so they consume disk space and contribute to the increase in the blockchain’s size, but

they are not stored in the UTXO set and therefore do not bloat the UTXO memory pool

and burden full nodes with the cost of more expensive RAM.

OP\_RETURN scripts look like this:

OP\_RETURN <data>

The data portion is limited to 40 bytes and most often represents a hash, such as the

output from the SHA256 algorithm (32 bytes). Many applications put a prefix in front

of the data to help identify the application. For example, the Proof of Existence digital

notarization service uses the 8-byte prefix “DOCPROOF,” which is ASCII encoded as

44f4350524f4f46 in hexadecimal.

Keep in mind that there is no “unlocking script” that corresponds to OP\_RETURN that

could possibly be used to “spend” an OP\_RETURN output. The whole point of OP\_RE

TURN is that you can’t spend the money locked in that output, and therefore it does not

need to be held in the UTXO set as potentially spendable—OP\_RETURN is *provably unspendable*.

OP\_RETURN is usually an output with a zero bitcoin amount, because any

bitcoin assigned to such an output is effectively lost forever. If an OP\_RETURN is encountered

by the script validation software, it results immediately in halting the execution

of the validation script and marking the transaction as invalid. Thus, if you accidentally

reference an OP\_RETURN output as an input in a transaction, that transaction is invalid.

Standard Transactions | 131

A standard transaction (one that conforms to the isStandard() checks) can have only

one OP\_RETURN output. However, a single OP\_RETURN output can be combined in a

transaction with outputs of any other type.

Pay-to-Script-Hash (P2SH)

Pay-to-script-hash (P2SH) was introduced in 2012 as a powerful new type of transaction

that greatly simplifies the use of complex transaction scripts. To explain the need for

P2SH, let’s look at a practical example.

In Chapter 1 we introduced Mohammed, an electronics importer based in Dubai. Mohammed’s

company uses bitcoin’s multi-signature feature extensively for its corporate

accounts. Multi-signature scripts are one of the most common uses of bitcoin’s advanced

scripting capabilities and are a very powerful feature. Mohammed’s company uses a

multi-signature script for all customer payments, known in accounting terms as “accounts

receivable,” or AR. With the multi-signature scheme, any payments made by

customers are locked in such a way that they require at least two signatures to release,

from Mohammed and one of his partners or from his attorney who has a backup key.

A multi-signature scheme like that offers corporate governance controls and protects

against theft, embezzlement, or loss.

The resulting script is quite long and looks like this:

2 <Mohammed's Public Key> <Partner1 Public Key> <Partner2 Public Key> <Partner3

Public Key> <Attorney Public Key> 5 OP\_CHECKMULTISIG

Although multi-signature scripts are a powerful feature, they are cumbersome to use.

Given the preceding script, Mohammed would have to communicate this script to every

customer prior to payment. Each customer would have to use special bitcoin wallet

software with the ability to create custom transaction scripts, and each customer would

have to understand how to create a transaction using custom scripts. Furthermore, the

resulting transaction would be about five times larger than a simple payment transaction,

because this script contains very long public keys. The burden of that extra-large

transaction would be borne by the customer in the form of fees. Finally, a large transaction

script like this would be carried in the UTXO set in RAM in every full node, until

it was spent. All of these issues make using complex output scripts difficult in practice.

Pay-to-script-hash (P2SH) was developed to resolve these practical difficulties and to

make the use of complex scripts as easy as a payment to a bitcoin address. With P2SH

payments, the complex locking script is replaced with its digital fingerprint, a cryptographic

hash. When a transaction attempting to spend the UTXO is presented later, it

must contain the script that matches the hash, in addition to the unlocking script. In

simple terms, P2SH means “pay to a script matching this hash, a script that will be

presented later when this output is spent.”

132 | Chapter 5: Transactions

In P2SH transactions, the locking script that is replaced by a hash is referred to as the

*redeem script* because it is presented to the system at redemption time rather than as a

locking script. Table 5-4 shows the script without P2SH and Table 5-5 shows the same

script encoded with P2SH.

*Table 5-4. Complex script without P2SH*

Locking Script 2 PubKey1 PubKey2 PubKey3 PubKey4 PubKey5 5 OP\_CHECKMULTISIG

Unlocking Script Sig1 Sig2

*Table 5-5. Complex script as P2SH*

Redeem Script 2 PubKey1 PubKey2 PubKey3 PubKey4 PubKey5 5 OP\_CHECKMULTISIG

Locking Script OP\_HASH160 <20-byte hash of redeem script> OP\_EQUAL

Unlocking Script Sig1 Sig2 redeem script

As you can see from the tables, with P2SH the complex script that details the conditions

for spending the output (redeem script) is not presented in the locking script. Instead,

only a hash of it is in the locking script and the redeem script itself is presented later, as

part of the unlocking script when the output is spent. This shifts the burden in fees and

complexity from the sender to the recipient (spender) of the transaction.

Let’s look at Mohammed’s company, the complex multi-signature script, and the resulting

P2SH scripts.

First, the multi-signature script that Mohammed’s company uses for all incoming payments

from customers:

2 <Mohammed's Public Key> <Partner1 Public Key> <Partner2 Public Key> <Partner3

Public Key> <Attorney Public Key> 5 OP\_CHECKMULTISIG

If the placeholders are replaced by actual public keys (shown here as 520-bit numbers

starting with 04) you can see that this script becomes very long:

2

04C16B8698A9ABF84250A7C3EA7EEDEF9897D1C8C6ADF47F06CF73370D74DCCA01CDCA79DCC5C395D7EEC6984D83F1F50C900A24DD47F

569FD4193AF5DE762C58704A2192968D8655D6A935BEAF2CA23E3FB87A3495E7AF308EDF08DAC3C1

FCBFC2C75B4B0F4D0B1B70CD2423657738C0C2B1D5CE65C97D78D0E34224858008E8B49047E63248

B75DB7379BE9CDA8CE5751D16485F431E46117B9D0C1837C9D5737812F393DA7D4420D7E1A9162F0

279CFC10F1E8E8F3020DECDBC3C0DD389D99779650421D65CBD7149B255382ED7F78E946580657EE

6FDA162A187543A9D85BAAA93A4AB3A8F044DADA618D087227440645ABE8A35DA8C5B73997AD343BE5C2AFD94A5043752580AFA1ECED3C68D446BCAB69AC0

BA7DF50D56231BE0AABF1FDEEC78A6A45E394BA29A1EDF518C022DD618DA7

74D207D137AAB59E0B000EB7ED238F4D800 5 OP\_CHECKMULTISIG

This entire script can instead be represented by a 20-byte cryptographic hash, by first

applying the SHA256 hashing algorithm and then applying the RIPEMD160 algorithm

on the result. The 20-byte hash of the preceding script is:

Standard Transactions | 133

54c557e07dde5bb6cb791c7a540e0a4796f5e97e

A P2SH transaction locks the output to this hash instead of the longer script, using the

locking script:

OP\_HASH160 54c557e07dde5bb6cb791c7a540e0a4796f5e97e OP\_EQUAL

which, as you can see, is much shorter. Instead of “pay to this 5-key multi-signature

script,” the P2SH equivalent transaction is “pay to a script with this hash.” A customer

making a payment to Mohammed’s company need only include this much shorter locking

script in his payment. When Mohammed wants to spend this UTXO, they must

present the original redeem script (the one whose hash locked the UTXO) and the

signatures necessary to unlock it, like this:

<Sig1> <Sig2> <2 PK1 PK2 PK3 PK4 PK5 5 OP\_CHECKMULTISIG>

The two scripts are combined in two stages. First, the redeem script is checked against

the locking script to make sure the hash matches:

<2 PK1 PK2 PK3 PK4 PK5 5 OP\_CHECKMULTISIG> OP\_HASH160 <redeem scriptHash>

OP\_EQUAL

If the redeem script hash matches, the unlocking script is executed on its own, to unlock

the redeem script:

<Sig1> <Sig2> 2 PK1 PK2 PK3 PK4 PK5 5 OP\_CHECKMULTISIG

Pay-to-script-hash addresses

Another important part of the P2SH feature is the ability to encode a script hash as an

address, as defined in BIP0013. P2SH addresses are Base58Check encodings of the 20-

byte hash of a script, just like bitcoin addresses are Base58Check encodings of the 20-

byte hash of a public key. P2SH addresses use the version prefix “5”, which results in

Base58Check-encoded addresses that start with a “3”. For example, Mohammed’s complex

script, hashed and Base58Check-encoded as a P2SH address becomes 39RF6JqA

BiHdYHkfChV6USGMe6Nsr66Gzw. Now, Mohammed can give this “address” to his customers

and they can use almost any bitcoin wallet to make a simple payment, as if it

were a bitcoin address. The 3 prefix gives them a hint that this is a special type of address,

one corresponding to a script instead of a public key, but otherwise it works in exactly

the same way as a payment to a bitcoin address.

P2SH addresses hide all of the complexity, so that the person making a payment does

not see the script.

Benefits of pay-to-script-hash

The pay-to-script-hash feature offers the following benefits compared to the direct use

of complex scripts in locking outputs:

134 | Chapter 5: Transactions

• Complex scripts are replaced by shorter fingerprints in the transaction output,

making the transaction smaller.

• Scripts can be coded as an address, so the sender and the sender’s wallet don’t need

complex engineering to implement P2SH.

• P2SH shifts the burden of constructing the script to the recipient, not the sender.

• P2SH shifts the burden in data storage for the long script from the output (which

is in the UTXO set and therefore affect memory) to the input (only stored on the

blockchain).

• P2SH shifts the burden in data storage for the long script from the present time

(payment) to a future time (when it is spent).

• P2SH shifts the transaction fee cost of a long script from the sender to the recipient,

who has to include the long redeem script to spend it.

Redeem script and isStandard validation

Prior to version 0.9.2 of the Bitcoin Core client, pay-to-script-hash was limited to the

standard types of bitcoin transaction scripts, by the isStandard() function. That means

that the redeem script presented in the spending transaction could only be one of the

standard types: P2PK, P2PKH, or multi-sig nature, excluding OP\_RETURN and P2SH

itself.

As of version 0.9.2 of the Bitcoin Core client, P2SH transactions can contain any valid

script, making the P2SH standard much more flexible and allowing for experimentation

with many novel and complex types of transactions.

Note that you are not able to put a P2SH inside a P2SH redeem script, because the P2SH

specification is not recursive. You are also still not able to use OP\_RETURN in a redeem

script because OP\_RETURN cannot be redeemed by definition.

Note that because the redeem script is not presented to the network until you attempt

to spend a P2SH output, if you lock an output with the hash of an invalid transaction

it will be processed regardless. However, you will not be able to spend it because the

spending transaction, which includes the redeem script, will not be accepted because it

is an invalid script. This creates a risk, because you can lock bitcoin in a P2SH that

cannot be spent later. The network will accept the P2SH encumbrance even if it corresponds

to an invalid redeem script, because the script hash gives no indication of the

script it represents.

Standard Transactions | 135

P2SH locking scripts contain the hash of a redeem script, which gives

no clues as to the content of the redeem script itself. The P2SH

transaction will be considered valid and accepted even if the redeem

script is invalid. You might accidentally lock bitcoin in such a

way that it cannot later be spent.

136 | Chapter 5: Transactions

CHAPTER 6

The Bitcoin Network

Peer-to-Peer Network Architecture

Bitcoin is structured as a peer-to-peer network architecture on top of the Internet. The

term peer-to-peer, or P2P, means that the computers that participate in the network are

peers to each other, that they are all equal, that there are no “special” nodes, and that all

nodes share the burden of providing network services. The network nodes interconnect

in a mesh network with a “flat” topology. There is no server, no centralized service, and

no hierarchy within the network. Nodes in a peer-to-peer network both provide and

consume services at the same time with reciprocity acting as the incentive for participation.

Peer-to-peer networks are inherently resilient, decentralized, and open. The

preeminent example of a P2P network architecture was the early Internet itself, where

nodes on the IP network were equal. Today’s Internet architecture is more hierarchical,

but the Internet Protocol still retains its flat-topology essence. Beyond bitcoin, the largest

and most successful application of P2P technologies is file sharing with Napster as

the pioneer and BitTorrent as the most recent evolution of the architecture.

Bitcoin’s P2P network architecture is much more than a topology choice. Bitcoin is a

peer-to-peer digital cash system by design, and the network architecture is both a reflection

and a foundation of that core characteristic. Decentralization of control is a core

design principle and that can only be achieved and maintained by a flat, decentralized

P2P consensus network.

The term “bitcoin network” refers to the collection of nodes running the bitcoin P2P

protocol. In addition to the bitcoin P2P protocol, there are other protocols such as

Stratum, which are used for mining and lightweight or mobile wallets. These additional

protocols are provided by gateway routing servers that access the bitcoin network using

the bitcoin P2P protocol, and then extend that network to nodes running other protocols.

For example, Stratum servers connect Stratum mining nodes via the Stratum protocol

to the main bitcoin network and bridge the Stratum protocol to the bitcoin P2P

137

protocol. We use the term “extended bitcoin network” to refer to the overall network

that includes the bitcoin P2P protocol, pool-mining protocols, the Stratum protocol,

and any other related protocols connecting the components of the bitcoin system.

Nodes Types and Roles

Although nodes in the bitcoin P2P network are equal, they may take on different roles

depending on the functionality they are supporting. A bitcoin node is a collection of

functions: routing, the blockchain database, mining, and wallet services. A full node

with all four of these functions is shown in Figure 6-1.

*Figure 6-1. A bitcoin network node with all four functions: wallet, miner, full blockchain*

*database, and network routing*

All nodes include the routing function to participate in the network and might include

other functionality. All nodes validate and propagate transactions and blocks, and discover

and maintain connections to peers. In the full-node example in Figure 6-1, the

routing function is indicated by an orange circle named “Network Routing Node.”

Some nodes, called full nodes, also maintain a complete and up-to-date copy of the

blockchain. Full nodes can autonomously and authoritatively verify any transaction

without external reference. Some nodes maintain only a subset of the blockchain and

verify transactions using a method called *simplified payment verification*, or SPV. These

nodes are known as SPV or lightweight nodes. In the full-node example in the figure,

the full-node blockchain database function is indicated by a blue circle named “Full

138 | Chapter 6: The Bitcoin Network

Blockchain.” In Figure 6-3, SPV nodes are drawn without the blue circle, showing that

they do not have a full copy of the blockchain.

Mining nodes compete to create new blocks by running specialized hardware to solve

the proof-of-work algorithm. Some mining nodes are also full nodes, maintaining a full

copy of the blockchain, while others are lightweight nodes participating in pool mining

and depending on a pool server to maintain a full node. The mining function is shown

in the full node as a black circle named “Miner.”

User wallets might be part of a full node, as is usually the case with desktop bitcoin

clients. Increasingly, many user wallets, especially those running on resourceconstrained

devices such as smartphones, are SPV nodes. The wallet function is shown

in Figure 6-1 as a green circle named “Wallet”.

In addition to the main node types on the bitcoin P2P protocol, there are servers and

nodes running other protocols, such as specialized mining pool protocols and lightweight

client-access protocols.

Figure 6-2 shows the most common node types on the extended bitcoin network.

The Extended Bitcoin Network

The main bitcoin network, running the bitcoin P2P protocol, consists of between 7,000

and 10,000 listening nodes running various versions of the bitcoin reference client (Bitcoin

Core) and a few hundred nodes running various other implementations of the

bitcoin P2P protocol, such as BitcoinJ, Libbitcoin, and btcd. A small percentage of the

nodes on the bitcoin P2P network are also mining nodes, competing in the mining

process, validating transactions, and creating new blocks. Various large companies interface

with the bitcoin network by running full-node clients based on the Bitcoin Core

client, with full copies of the blockchain and a network node, but without mining or

wallet functions. These nodes act as network edge routers, allowing various other services

(exchanges, wallets, block explorers, merchant payment processing) to be built on

top.

The extended bitcoin network includes the network running the bitcoin P2P protocol,

described earlier, as well as nodes running specialized protocols. Attached to the main

bitcoin P2P network are a number of pool servers and protocol gateways that connect

nodes running other protocols. These other protocol nodes are mostly pool mining

nodes (see Chapter 8) and lightweight wallet clients, which do not carry a full copy of

the blockchain.

Figure 6-3 shows the extended bitcoin network with the various types of nodes, gateway

servers, edge routers, and wallet clients and the various protocols they use to connect

to each other.

The Extended Bitcoin Network | 139

*Figure 6-2. Different types of nodes on the extended bitcoin network*

140 | Chapter 6: The Bitcoin Network

*Figure 6-3. The extended bitcoin network showing various node types, gateways, and*

*protocols*

The Extended Bitcoin Network | 141

Network Discovery

When a new node boots up, it must discover other bitcoin nodes on the network in

order to participate. To start this process, a new node must discover at least one existing

node on the network and connect to it. The geographic location of other nodes is irrelevant;

the bitcoin network topology is not geographically defined. Therefore, any

existing bitcoin nodes can be selected at random.

To connect to a known peer, nodes establish a TCP connection, usually to port 8333

(the port generally known as the one used by bitcoin), or an alternative port if one is

provided. Upon establishing a connection, the node will start a “handshake” (see

Figure 6-4) by transmitting a version message, which contains basic identifying information,

including:

PROTOCOL\_VERSION

A constant that defines the bitcoin P2P protocol version the client “speaks” (e.g.,

70002)

nLocalServices

A list of local services supported by the node, currently just NODE\_NETWORK

nTime

The current time

addrYou

The IP address of the remote node as seen from this node

addrMe

The IP address of the local node, as discovered by the local node

subver

A sub-version showing the type of software running on this node (e.g., “/Satoshi:

0.9.2.1/”)+

BestHeight

The block height of this node’s blockchain

(See GitHub for an example of the version network message.)

The peer node responds with verack to acknowledge and establish a connection, and

optionally sends its own version message if it wishes to reciprocate the connection and

connect back as a peer.

How does a new node find peers? Although there are no special nodes in bitcoin, there

are some long-running stable nodes that are listed in the client as *seed nodes*. Although

a new node does not have to connect with the seed nodes, it can use them to quickly

discover other nodes in the network. In the Bitcoin Core client, the option to use the

seed nodes is controlled by the option switch -dnsseed, which is set to 1, to use the seed

142 | Chapter 6: The Bitcoin Network

nodes, by default. Alternatively, a bootstrapping node that knows nothing of the network

must be given the IP address of at least one bitcoin node, after which it can establish

connections through further introductions. The command-line argument -seednode

can be used to connect to one node just for introductions, using it as a DNS seed. After

the initial seed node is used to form introductions, the client will disconnect from it and

use the newly discovered peers.

*Figure 6-4. The initial handshake between peers*

Once one or more connections are established, the new node will send an addr message

containing its own IP address to its neighbors. The neighbors will, in turn, forward the

addr message to their neighbors, ensuring that the newly connected node becomes well

known and better connected. Additionally, the newly connected node can send ge

taddr to the neighbors, asking them to return a list of IP addresses of other peers. That

way, a node can find peers to connect to and advertise its existence on the network for

other nodes to find it. Figure 6-5 shows the address discovery protocol.

Network Discovery | 143

*Figure 6-5. Address propagation and discovery*

A node must connect to a few different peers in order to establish diverse paths into the

bitcoin network. Paths are not reliable—nodes come and go—and so the node must

continue to discover new nodes as it loses old connections as well as assist other nodes

when they bootstrap. Only one connection is needed to bootstrap, because the first node

can offer introductions to its peer nodes and those peers can offer further introductions.

It’s also unnecessary and wasteful of network resources to connect to more than a

handful of nodes. After bootstrapping, a node will remember its most recent successful

peer connections, so that if it is rebooted it can quickly reestablish connections with its

former peer network. If none of the former peers respond to its connection request, the

node can use the seed nodes to bootstrap again.

On a node running the Bitcoin Core client, you can list the peer connections with the

command getpeerinfo:

$ bitcoin-cli getpeerinfo

[

{

**"addr"** : "85.213.199.39:8333",

**"services"** : "00000001",

**"lastsend"** : 1405634126,

**"lastrecv"** : 1405634127,

**"bytessent"** : 23487651,

**"bytesrecv"** : 138679099,

**"conntime"** : 1405021768,

**"pingtime"** : 0.00000000,

**"version"** : 70002,

**"subver"** : "/Satoshi:0.9.2.1/",

144 | Chapter 6: The Bitcoin Network

**"inbound"** : **false**,

**"startingheight"** : 310131,

**"banscore"** : 0,

**"syncnode"** : **true**

},

{

**"addr"** : "58.23.244.20:8333",

**"services"** : "00000001",

**"lastsend"** : 1405634127,

**"lastrecv"** : 1405634124,

**"bytessent"** : 4460918,

**"bytesrecv"** : 8903575,

**"conntime"** : 1405559628,

**"pingtime"** : 0.00000000,

**"version"** : 70001,

**"subver"** : "/Satoshi:0.8.6/",

**"inbound"** : **false**,

**"startingheight"** : 311074,

**"banscore"** : 0,

**"syncnode"** : **false**

}

]

To override the automatic management of peers and to specify a list of IP addresses,

users can provide the option -connect=<IPAddress> and specify one or more IP addresses.

If this option is used, the node will only connect to the selected IP addresses,

instead of discovering and maintaining the peer connections automatically.

If there is no traffic on a connection, nodes will periodically send a message to maintain

the connection. If a node has not communicated on a connection for more than 90

minutes, it is assumed to be disconnected and a new peer will be sought. Thus, the

network dynamically adjusts to transient nodes and network problems, and can organically

grow and shrink as needed without any central control.

Full Nodes

Full nodes are nodes that maintain a full blockchain with all transactions. More accurately,

they probably should be called “full blockchain nodes.” In the early years of bitcoin,

all nodes were full nodes and currently the Bitcoin Core client is a full blockchain

node. In the past two years, however, new forms of bitcoin clients have been introduced

that do not maintain a full blockchain but run as lightweight clients. We’ll examine these

in more detail in the next section.

Full blockchain nodes maintain a complete and up-to-date copy of the bitcoin blockchain

with all the transactions, which they independently build and verify, starting with

the very first block (genesis block) and building up to the latest known block in the

network. A full blockchain node can independently and authoritatively verify any

transaction without recourse or reliance on any other node or source of information.

Full Nodes | 145

The full blockchain node relies on the network to receive updates about new blocks of

transactions, which it then verifies and incorporates into its local copy of the blockchain.

Running a full blockchain node gives you the pure bitcoin experience: independent

verification of all transactions without the need to rely on, or trust, any other systems.

It’s easy to tell if you’re running a full node because it requires 20+ gigabytes of persistent

storage (disk space) to store the full blockchain. If you need a lot of disk and it takes

two to three days to sync to the network, you are running a full node. That is the price

of complete independence and freedom from central authority.

There are a few alternative implementations of full blockchain bitcoin clients, built using

different programming languages and software architectures. However, the most common

implementation is the reference client Bitcoin Core, also known as the Satoshi

client. More than 90% of the nodes on the bitcoin network run various versions of

Bitcoin Core. It is identified as “Satoshi” in the sub-version string sent in the version

message and shown by the command getpeerinfo as we saw earlier; for example, /

Satoshi:0.8.6/.

Exchanging “Inventory”

The first thing a full node will do once it connects to peers is try to construct a complete

blockchain. If it is a brand-new node and has no blockchain at all, it only knows one

block, the genesis block, which is statically embedded in the client software. Starting

with block #0 (the genesis block), the new node will have to download hundreds of

thousands of blocks to synchronize with the network and re-establish the full blockchain.

The process of syncing the blockchain starts with the version message, because that

contains BestHeight, a node’s current blockchain height (number of blocks). A node

will see the version messages from its peers, know how many blocks they each have,

and be able to compare to how many blocks it has in its own blockchain. Peered nodes

will exchange a%605.420%%% getblocks message that contains the hash (fingerprint)

of the top block on their local blockchain. One of the peers will be able to identify the

received hash as belonging to a block that is not at the top, but rather belongs to an older

block, thus deducing that its own local blockchain is longer than its peer’s.

The peer that has the longer blockchain has more blocks than the other node and can

identify which blocks the other node needs in order to “catch up.” It will identify the

first 500 blocks to share and transmit their hashes using an inv (inventory) message.

The node missing these blocks will then retrieve them, by issuing a series of getdata

messages requesting the full block data and identifying the requested blocks using the

hashes from the inv message.

146 | Chapter 6: The Bitcoin Network

Let’s assume, for example, that a node only has the genesis block. It will then receive an

inv message from its peers containing the hashes of the next 500 blocks in the chain. It

will start requesting blocks from all of its connected peers, spreading the load and ensuring

that it doesn’t overwhelm any peer with requests. The node keeps track of how

many blocks are “in transit” per peer connection, meaning blocks that it has requested

but not received, checking that it does not exceed a limit (MAX\_BLOCKS\_IN\_TRANS

IT\_PER\_PEER). This way, if it needs a lot of blocks, it will only request new ones as

previous requests are fulfilled, allowing the peers to control the pace of updates and not

overwhelming the network. As each block is received, it is added to the blockchain, as

we will see in Chapter 7. As the local blockchain is gradually built up, more blocks are

requested and received, and the process continues until the node catches up to the rest

of the network.

This process of comparing the local blockchain with the peers and retrieving any missing

blocks happens any time a node goes offline for any period of time. Whether a node has

been offline for a few minutes and is missing a few blocks, or a month and is missing a

few thousand blocks, it starts by sending getblocks, gets an inv response, and starts

downloading the missing blocks. Figure 6-6 shows the inventory and block propagation

protocol.

Simplified Payment Verification (SPV) Nodes

Not all nodes have the ability to store the full blockchain. Many bitcoin clients are

designed to run on space- and power-constrained devices, such as smartphones, tablets,

or embedded systems. For such devices, a *simplified payment verification* (SPV) method

is used to allow them to operate without storing the full blockchain. These types of

clients are called SPV clients or lightweight clients. As bitcoin adoption surges, the SPV

node is becoming the most common form of bitcoin node, especially for bitcoin wallets.

SPV nodes download only the block headers and do not download the transactions

included in each block. The resulting chain of blocks, without transactions, is 1,000

times smaller than the full blockchain. SPV nodes cannot construct a full picture of all

the UTXOs that are available for spending because they do not know about all the

transactions on the network. SPV nodes verify transactions using a slightly different

methodology that relies on peers to provide partial views of relevant parts of the blockchain

on demand.

Simplified Payment Verification (SPV) Nodes | 147

*Figure 6-6. Node synchronizing the blockchain by retrieving blocks from a peer*

As an analogy, a full node is like a tourist in a strange city, equipped with a detailed map

of every street and every address. By comparison, an SPV node is like a tourist in a

strange city asking random strangers for turn-by-turn directions while knowing only

one main avenue. Although both tourists can verify the existence of a street by visiting

it, the tourist without a map doesn’t know what lies down any of the side streets and

doesn’t know what other streets exist. Positioned in front of 23 Church Street, the tourist

without a map cannot know if there are a dozen other “23 Church Street” addresses in

the city and whether this is the right one. The mapless tourist’s best chance is to ask

enough people and hope some of them are not trying to mug him.

Simplified payment verification verifies transactions by reference to their *depth* in the

blockchain instead of their *height*. Whereas a full blockchain node will construct a fully

verified chain of thousands of blocks and transactions reaching down the blockchain

(back in time) all the way to the genesis block, an SPV node will verify the chain of all

blocks (but not all transactions) and link that chain to the transaction of interest.

148 | Chapter 6: The Bitcoin Network

For example, when examining a transaction in block 300,000, a full node links all 300,000

blocks down to the genesis block and builds a full database of UTXO, establishing the

validity of the transaction by confirming that the UTXO remains unspent. An SPV node

cannot validate whether the UTXO is unspent. Instead, the SPV node will establish a

link between the transaction and the block that contains it, using a *merkle path* (see

“Merkle Trees” on page 164). Then, the SPV node waits until it sees the six blocks 300,001

through 300,006 piled on top of the block containing the transaction and verifies it by

establishing its depth under blocks 300,006 to 300,001. The fact that other nodes on the

network accepted block 300,000 and then did the necessary work to produce six more

blocks on top of it is proof, by proxy, that the transaction was not a double-spend.

An SPV node cannot be persuaded that a transaction exists in a block when the transaction

does not in fact exist. The SPV node establishes the existence of a transaction in

a block by requesting a merkle path proof and by validating the proof of work in the

chain of blocks. However, a transaction’s existence can be “hidden” from an SPV node.

An SPV node can definitely prove that a transaction exists but cannot verify that a

transaction, such as a double-spend of the same UTXO, doesn’t exist because it doesn’t

have a record of all transactions. This vulnerability can be used in a denial-of-service

attack or for a double-spending attack against SPV nodes. To defend against this, an

SPV node needs to connect randomly to several nodes, to increase the probability that

it is in contact with at least one honest node. This need to randomly connect means that

SPV nodes also are vulnerable to network partitioning attacks or Sybil attacks, where

they are connected to fake nodes or fake networks and do not have access to honest

nodes or the real bitcoin network.

For most practical purposes, well-connected SPV nodes are secure enough, striking the

right balance between resource needs, practicality, and security. For infallible security,

however, nothing beats running a full blockchain node.

A full blockchain node verifies a transaction by checking the entire

chain of thousands of blocks below it in order to guarantee that the

UTXO is not spent, whereas an SPV node checks how deep the block

is buried by a handful of blocks above it.

To get the block headers, SPV nodes use a getheaders message instead of getblocks.

The responding peer will send up to 2,000 block headers using a single headers message.

The process is otherwise the same as that used by a full node to retrieve full blocks. SPV

nodes also set a filter on the connection to peers, to filter the stream of future blocks

and transactions sent by the peers. Any transactions of interest are retrieved using a

getdata request. The peer generates a tx message containing the transactions, in response.

Figure 6-7 shows the synchronization of block headers.

Simplified Payment Verification (SPV) Nodes | 149

*Figure 6-7. SPV node synchronizing the block headers*

Because SPV nodes need to retrieve specific transactions in order to selectively verify

them, they also create a privacy risk. Unlike full blockchain nodes, which collect all

transactions within each block, the SPV node’s requests for specific data can inadvertently

reveal the addresses in their wallet. For example, a third party monitoring a network

could keep track of all the transactions requested by a wallet on an SPV node and

use those to associate bitcoin addresses with the user of that wallet, destroying the user’s

privacy.

Shortly after the introduction of SPV/lightweight nodes, the bitcoin developers added

a feature called *bloom filters* to address the privacy risks of SPV nodes. Bloom filters

allow SPV nodes to receive a subset of the transactions without revealing precisely which

addresses they are interested in, through a filtering mechanism that uses probabilities

rather than fixed patterns.

Bloom Filters

A bloom filter is a probabilistic search filter, a way to describe a desired pattern without

specifying it exactly. Bloom filters offer an efficient way to express a search pattern while

protecting privacy. They are used by SPV nodes to ask their peers for transactions

matching a specific pattern, without revealing exactly which addresses they are searching

for.

150 | Chapter 6: The Bitcoin Network

In our previous analogy, a tourist without a map is asking for directions to a specific

address, “23 Church St.” If she asks strangers for directions to this street, she inadvertently

reveals her destination. A bloom filter is like asking, “Are there any streets in this

neighborhood whose name ends in R-C-H?” A question like that reveals slightly less

about the desired destination than asking for “23 Church St.” Using this technique, a

tourist could specify the desired address in more detail as “ending in U-R-C-H” or less

detail as “ending in H.” By varying the precision of the search, the tourist reveals more

or less information, at the expense of getting more or less specific results. If she asks a

less specific pattern, she gets a lot more possible addresses and better privacy, but many

of the results are irrelevant. If she asks for a very specific pattern, she gets fewer results

but loses privacy.

Bloom filters serve this function by allowing an SPV node to specify a search pattern

for transactions that can be tuned toward precision or privacy. A more specific bloom

filter will produce accurate results, but at the expense of revealing what addresses are

used in the user’s wallet. A less specific bloom filter will produce more data about more

transactions, many irrelevant to the node, but will allow the node to maintain better

privacy.

An SPV node will initialize a bloom filter as “empty” and in that state the bloom filter

will not match any patterns. The SPV node will then make a list of all the addresses in

its wallet and create a search pattern matching the transaction output that corresponds

to each address. Usually, the search pattern is a pay-to-public-key-hash script that is the

expected locking script that will be present in any transaction paying to the public-keyhash

(address). If the SPV node is tracking the balance of a P2SH address, the search

pattern will be a pay-to-script-hash script, instead. The SPV node then adds each of the

search patterns to the bloom filter, so that the bloom filter can recognize the search

pattern if it is present in a transaction. Finally, the bloom filter is sent to the peer and

the peer uses it to match transactions for transmission to the SPV node.

Bloom filters are implemented as a variable-size array of N binary digits (a bit field) and

a variable number of M hash functions. The hash functions are designed to always

produce an output that is between 1 and N, corresponding to the array of binary digits.

The hash functions are generated deterministically, so that any node implementing a

bloom filter will always use the same hash functions and get the same results for a specific

input. By choosing different length (N) bloom filters and a different number (M) of

hash functions, the bloom filter can be tuned, varying the level of accuracy and therefore

privacy.

In Figure 6-8, we use a very small array of 16 bits and a set of three hash functions to

demonstrate how bloom filters work.

Bloom Filters | 151

*Figure 6-8. An example of a simplistic bloom filter, with a 16-bit field and three hash*

*functions*

The bloom filter is initialized so that the array of bits is all zeros. To add a pattern to the

bloom filter, the pattern is hashed by each hash function in turn. Applying the first hash

function to the input results in a number between 1 and N. The corresponding bit in

the array (indexed from 1 to N) is found and set to 1, thereby recording the output of

the hash function. Then, the next hash function is used to set another bit and so on.

Once all M hash functions have been applied, the search pattern will be “recorded” in

the bloom filter as M bits that have been changed from 0 to 1.

Figure 6-9 is an example of adding a pattern “A” to the simple bloom filter shown in

Figure 6-8.

Adding a second pattern is as simple as repeating this process. The pattern is hashed by

each hash function in turn and the result is recorded by setting the bits to 1. Note that

as a bloom filter is filled with more patterns, a hash function result might coincide with

a bit that is already set to 1, in which case the bit is not changed. In essence, as more

patterns record on overlapping bits, the bloom filter starts to become saturated with

more bits set to 1 and the accuracy of the filter decreases. This is why the filter is a

probabilistic data structure—it gets less accurate as more patterns are added. The accuracy

depends on the number of patterns added versus the size of the bit array (N) and

number of hash functions (M). A larger bit array and more hash functions can record

more patterns with higher accuracy. A smaller bit array or fewer hash functions will

record fewer patterns and produce less accuracy.

152 | Chapter 6: The Bitcoin Network

*Figure 6-9. Adding a pattern “A” to our simple bloom filter*

Figure 6-10 is an example of adding a second pattern “B” to the simple bloom filter.

*Figure 6-10. Adding a second pattern “B” to our simple bloom filter*

To test if a pattern is part of a bloom filter, the pattern is hashed by each hash function

and the resulting bit pattern is tested against the bit array. If all the bits indexed by the

hash functions are set to 1, then the pattern is *probably* recorded in the bloom filter.

Bloom Filters | 153

Because the bits may be set because of overlap from multiple patterns, the answer is not

certain, but is rather probabilistic. In simple terms, a bloom filter positive match is a

“Maybe, Yes.”

Figure 6-11 is an example of testing the existence of pattern “X” in the simple bloom

filter. The corresponding bits are set to 1, so the pattern is probably a match.

*Figure 6-11. Testing the existence of pattern “X” in the bloom filter. The result is probabilistic*

*positive match, meaning “Maybe.”*

On the contrary, if a pattern is tested against the bloom filter and any one of the bits is

set to 0, this proves that the pattern was not recorded in the bloom filter. A negative

result is not a probability, it is a certainty. In simple terms, a negative match on a bloom

filter is a “Definitely Not!”

Figure 6-12 is an example of testing the existence of pattern “Y” in the simple bloom

filter. One of the corresponding bits is set to 0, so the pattern is definitely not a match.

154 | Chapter 6: The Bitcoin Network

*Figure 6-12. Testing the existence of pattern “Y” in the bloom filter. The result is a definitive*

*negative match, meaning “Definitely Not!”*

Bitcoin’s implementation of bloom filters is described in Bitcoin Improvement Proposal

37 (BIP0037). See Appendix B or visit GitHub.

Bloom Filters and Inventory Updates

Bloom filters are used to filter the transactions (and blocks containing them) that an

SPV node receives from its peers. SPV nodes will create a filter that matches only the

addresses held in the SPV node’s wallet. The SPV node will then send a filterload

message to the peer, containing the bloom filter to use on the connection. After a filter

is established, the peer will then test each transaction’s outputs against the bloom filter.

Only transactions that match the filter are sent to the node.

In response to a getdata message from the node, peers will send a merkleblock message

that contains only block headers for blocks matching the filter and a merkle path (see

“Merkle Trees” on page 164) for each matching transaction. The peer will then also send

tx messages containing the transactions matched by the filter.

The node setting the bloom filter can interactively add patterns to the filter by sending

a filteradd message. To clear the bloom filter, the node can send a filterclear

message. Because it is not possible to remove a pattern from a bloom filter, a node has

to clear and resend a new bloom filter if a pattern is no longer desired.

Bloom Filters and Inventory Updates | 155

Transaction Pools

Almost every node on the bitcoin network maintains a temporary list of unconfirmed

transactions called the *memory pool*, or *transaction pool*. Nodes use this pool to keep

track of transactions that are known to the network but are not yet included in the

blockchain. For example, a node that holds a user’s wallet will use the transaction pool

to track incoming payments to the user’s wallet that have been received on the network

but are not yet confirmed.

As transactions are received and verified, they are added to the transaction pool and

relayed to the neighboring nodes to propagate on the network.

Some node implementations also maintain a separate pool of orphaned transactions. If

a transaction’s inputs refer to a transaction that is not yet known, such as a missing

parent, the orphan transaction will be stored temporarily in the orphan pool until the

parent transaction arrives.

When a transaction is added to the transaction pool, the orphan pool is checked for any

orphans that reference this transaction’s outputs (its children). Any matching orphans

are then validated. If valid, they are removed from the orphan pool and added to the

transaction pool, completing the chain that started with the parent transaction. In light

of the newly added transaction, which is no longer an orphan, the process is repeated

recursively looking for any further descendants, until no more descendants are found.

Through this process, the arrival of a parent transaction triggers a cascade reconstruction

of an entire chain of interdependent transactions by re-uniting the orphans with

their parents all the way down the chain.

Both the transaction pool and orphan pool (where implemented) are stored in local

memory and are not saved on persistent storage; rather, they are dynamically populated

from incoming network messages. When a node starts, both pools are empty and are

gradually populated with new transactions received on the network.

Some implementations of the bitcoin client also maintain a UTXO database or UTXO

pool, which is the set of all unspent outputs on the blockchain. Although the name

“UTXO pool” sounds similar to the transaction pool, it represents a different set of data.

Unlike the transaction and orphan pools, the UTXO pool is not initialized empty but

instead contains millions of entries of unspent transaction outputs, including some

dating back to 2009. The UTXO pool may be housed in local memory or as an indexed

database table on persistent storage.

Whereas the transaction and orphan pools represent a single node’s local perspective

and might vary significantly from node to node depending upon when the node was

started or restarted, the UTXO pool represents the emergent consensus of the network

and therefore will vary little between nodes. Furthermore, the transaction and orphan

156 | Chapter 6: The Bitcoin Network

pools only contain unconfirmed transactions, while the UTXO pool only contains confirmed

outputs.

Alert Messages

Alert messages are a seldom used function, but are nevertheless implemented in most

nodes. Alert messages are bitcoin’s “emergency broadcast system,” a means by which

the core bitcoin developers can send an emergency text message to all bitcoin nodes.

This feature is implemented to allow the core developer team to notify all bitcoin users

of a serious problem in the bitcoin network, such as a critical bug that requires user

action. The alert system has only been used a handful of times, most notably in early

2013 when a critical database bug caused a multiblock fork to occur in the bitcoin

blockchain.

Alert messages are propagated by the alert message. The alert message contains several

fields, including:

*ID*

An alert identified so that duplicate alerts can be detected

*Expiration*

A time after which the alert expires

*RelayUntil*

A time after which the alert should not be relayed

*MinVer, MaxVer*

The range of bitcoin protocol versions that this alert applies to

*subVer*

The client software version that this alert applies to

*Priority*

An alert priority level, currently unused

Alerts are cryptographically signed by a public key. The corresponding private key is

held by a few select members of the core development team. The digital signature ensures

that fake alerts will not be propagated on the network.

Each node receiving this alert message will verify it, check for expiration, and propagate

it to all its peers, thus ensuring rapid propagation across the entire network. In addition

to propagating the alert, the nodes might implement a user interface function to present

the alert to the user.

In the Bitcoin Core client, the alert is configured with the command-line option -

alertnotify, which specifies a command to run when an alert is received. The alert

message is passed as a parameter to the alertnotify command. Most commonly, the

Alert Messages | 157

alertnotify command is set to generate an email message to the administrator of the

node, containing the alert message. The alert is also displayed as a pop-up dialog in the

graphical user interface (bitcoin-Qt) if it is running.

Other implementations of the bitcoin protocol might handle the alert in different ways.

Many hardware-embedded bitcoin mining systems do not implement the alert message

function because they have no user interface. It is strongly recommended that miners

running such mining systems subscribe to alerts via a mining pool operator or by running

a lightweight node just for alert purposes.

158 | Chapter 6: The Bitcoin Network

CHAPTER 7

The Blockchain

Introduction

The blockchain data structure is an ordered, back-linked list of blocks of transactions.

The blockchain can be stored as a flat file, or in a simple database. The Bitcoin Core

client stores the blockchain metadata using Google’s LevelDB database. Blocks are

linked “back,” each referring to the previous block in the chain. The blockchain is often

visualized as a vertical stack, with blocks layered on top of each other and the first block

serving as the foundation of the stack. The visualization of blocks stacked on top of each

other results in the use of terms such as “height” to refer to the distance from the first

block, and “top” or “tip” to refer to the most recently added block.

Each block within the blockchain is identified by a hash, generated using the SHA256

cryptographic hash algorithm on the header of the block. Each block also references a

previous block, known as the *parent* block, through the “previous block hash” field in

the block header. In other words, each block contains the hash of its parent inside its

own header. The sequence of hashes linking each block to its parent creates a chain

going back all the way to the first block ever created, known as the *genesis block*.

Although a block has just one parent, it can temporarily have multiple children. Each

of the children refers to the same block as its parent and contains the same (parent) hash

in the “previous block hash” field. Multiple children arise during a blockchain “fork,” a

temporary situation that occurs when different blocks are discovered almost simultaneously

by different miners (see “Blockchain Forks” on page 199). Eventually, only one

child block becomes part of the blockchain and the “fork” is resolved. Even though a

block may have more than one child, each block can have only one parent. This is because

a block has one single “previous block hash” field referencing its single parent.

The “previous block hash” field is inside the block header and thereby affects the *current*

block’s hash. The child’s own identity changes if the parent’s identity changes. When

the parent is modified in any way, the parent’s hash changes. The parent’s changed hash

159

necessitates a change in the “previous block hash” pointer of the child. This in turn

causes the child’s hash to change, which requires a change in the pointer of the grandchild,

which in turn changes the grandchild, and so on. This cascade effect ensures that

once a block has many generations following it, it cannot be changed without forcing

a recalculation of all subsequent blocks. Because such a recalculation would require

enormous computation, the existence of a long chain of blocks makes the blockchain’s

deep history immutable, which is a key feature of bitcoin’s security.

One way to think about the blockchain is like layers in a geological formation, or glacier

core sample. The surface layers might change with the seasons, or even be blown away

before they have time to settle. But once you go a few inches deep, geological layers

become more and more stable. By the time you look a few hundred feet down, you are

looking at a snapshot of the past that has remained undisturbed for millions of years.

In the blockchain, the most recent few blocks might be revised if there is a chain recalculation

due to a fork. The top six blocks are like a few inches of topsoil. But once you

go more deeply into the blockchain, beyond six blocks, blocks are less and less likely to

change. After 100 blocks back there is so much stability that the coinbase transaction

—the transaction containing newly mined bitcoins—can be spent. A few thousand

blocks back (a month) and the blockchain is settled history. It will never change.

Structure of a Block

A block is a container data structure that aggregates transactions for inclusion in the

public ledger, the blockchain. The block is made of a header, containing metadata, followed

by a long list of transactions that make up the bulk of its size. The block header

is 80 bytes, whereas the average transaction is at least 250 bytes and the average block

contains more than 500 transactions. A complete block, with all transactions, is therefore

1,000 times larger than the block header. Table 7-1 describes the structure of a block.

*Table 7-1. The structure of a block*

Size Field Description

4 bytes Block Size The size of the block, in bytes, following this field

80 bytes Block Header Several fields form the block header

1-9 bytes (VarInt) Transaction Counter How many transactions follow

Variable Transactions The transactions recorded in this block

Block Header

The block header consists of three sets of block metadata. First, there is a reference to

a previous block hash, which connects this block to the previous block in the blockchain.

The second set of metadata, namely the *difficulty*, *timestamp*, and *nonce*, relate to the

mining competition, as detailed in Chapter 8. The third piece of metadata is the merkle

160 | Chapter 7: The Blockchain

tree root, a data structure used to efficiently summarize all the transactions in the block.

Table 7-2 describes the structure of a block header.

*Table 7-2. The structure of the block header*

Size Field Description

4 bytes Version A version number to track software/protocol upgrades

32 bytes Previous Block Hash A reference to the hash of the previous (parent) block in the chain

32 bytes Merkle Root A hash of the root of the merkle tree of this block’s transactions

4 bytes Timestamp The approximate creation time of this block (seconds from Unix Epoch)

4 bytes Difficulty Target The proof-of-work algorithm difficulty target for this block

4 bytes Nonce A counter used for the proof-of-work algorithm

The nonce, difficulty target, and timestamp are used in the mining process and will be

discussed in more detail in Chapter 8.

Block Identifiers: Block Header Hash and Block Height

The primary identifier of a block is its cryptographic hash, a digital fingerprint, made

by hashing the block header twice through the SHA256 algorithm. The resulting 32-

byte hash is called the *block hash* but is more accurately the *block header hash*,

because only the block header is used to compute it. For example,

000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f is the

block hash of the first bitcoin block ever created. The block hash identifies a block

uniquely and unambiguously and can be independently derived by any node by simply

hashing the block header.

Note that the block hash is not actually included inside the block’s data structure, neither

when the block is transmitted on the network, nor when it is stored on a node’s persistence

storage as part of the blockchain. Instead, the block’s hash is computed by each

node as the block is received from the network. The block hash might be stored in a

separate database table as part of the block’s metadata, to facilitate indexing and faster

retrieval of blocks from disk.

A second way to identify a block is by its position in the blockchain, called the

*block height*. The first block ever created is at block height 0 (zero) and is the

same block that was previously referenced by the following block hash

000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f. A block

can thus be identified two ways: by referencing the block hash or by referencing the

block height. Each subsequent block added “on top” of that first block is one position

“higher” in the blockchain, like boxes stacked one on top of the other. The block height

on January 1, 2014, was approximately 278,000, meaning there were 278,000 blocks

stacked on top of the first block created in January 2009.

Block Identifiers: Block Header Hash and Block Height | 161

Unlike the block hash, the block height is not a unique identifier. Although a single block

will always have a specific and invariant block height, the reverse is not true—the block

height does not always identify a single block. Two or more blocks might have the same

block height, competing for the same position in the blockchain. This scenario is discussed

in detail in the section “Blockchain Forks” on page 199. The block height is also

not a part of the block’s data structure; it is not stored within the block. Each node

dynamically identifies a block’s position (height) in the blockchain when it is received

from the bitcoin network. The block height might also be stored as metadata in an

indexed database table for faster retrieval.

A block’s *block hash* always identifies a single block uniquely. A block

also always has a specific *block height*. However, it is not always the

case that a specific block height can identify a single block. Rather,

two or more blocks might compete for a single position in the blockchain.

The Genesis Block

The first block in the blockchain is called the genesis block and was created in 2009. It

is the common ancestor of all the blocks in the blockchain, meaning that if you start at

any block and follow the chain backward in time, you will eventually arrive at the genesis

block.

Every node always starts with a blockchain of at least one block because the genesis

block is statically encoded within the bitcoin client software, such that it cannot be

altered. Every node always “knows” the genesis block’s hash and structure, the fixed time

it was created, and even the single transaction within. Thus, every node has the starting

point for the blockchain, a secure “root” from which to build a trusted blockchain.

See the statically encoded genesis block inside the Bitcoin Core client, in chainparams.

cpp.

The following identifier hash belongs to the genesis block:

000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f

You can search for that block hash in any block explorer website, such as blockchain.info,

and you will find a page describing the contents of this block, with a URL containing

that hash:

*https://blockchain.info/block/*

*000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f*

*https://blockexplorer.com/block/*

*000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f*

162 | Chapter 7: The Blockchain

Using the Bitcoin Core reference client on the command line:

$ bitcoind getblock

000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f

{

**"hash"** : "000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f",

**"confirmations"** : 308321,

**"size"** : 285,

**"height"** : 0,

**"version"** : 1,

**"merkleroot"** : "4a5e1e4baab89f3a32518a88c31bc87f618f76673e2cc77ab2127b7afde

da33b",

**"tx"** : [

"4a5e1e4baab89f3a32518a88c31bc87f618f76673e2cc77ab2127b7afdeda33b"

],

**"time"** : 1231006505,

**"nonce"** : 2083236893,

**"bits"** : "1d00ffff",

**"difficulty"** : 1.00000000,

**"nextblockhash"** :

"00000000839a8e6886ab5951d76f411475428afc90947ee320161bbf18eb6048"

}

The genesis block contains a hidden message within it. The coinbase transaction input

contains the text “The Times 03/Jan/2009 Chancellor on brink of second bailout for

banks.” This message was intended to offer proof of the earliest date this block was

created, by referencing the headline of the British newspaper *The Times*. It also serves

as a tongue-in-cheek reminder of the importance of an independent monetary system,

with bitcoin’s launch occurring at the same time as an unprecedented worldwide monetary

crisis. The message was embedded in the first block by Satoshi Nakamoto, bitcoin’s

creator.

Linking Blocks in the Blockchain

Bitcoin full nodes maintain a local copy of the blockchain, starting at the genesis block.

The local copy of the blockchain is constantly updated as new blocks are found and used

to extend the chain. As a node receives incoming blocks from the network, it will validate

these blocks and then link them to the existing blockchain. To establish a link, a node

will examine the incoming block header and look for the “previous block hash.”

Let’s assume, for example, that a node has 277,314 blocks in the local copy of the blockchain.

The last block the node knows about is block 277,314, with a block header hash

of 00000000000000027e7ba6fe7bad39faf3b5a83daed765f05f7d1b71a1632249.

The bitcoin node then receives a new block from the network, which it parses as follows:

{

**"size"** : 43560,

**"version"** : 2,

Linking Blocks in the Blockchain | 163

**"previousblockhash"** :

"00000000000000027e7ba6fe7bad39faf3b5a83daed765f05f7d1b71a1632249",

**"merkleroot"** :

"5e049f4030e0ab2debb92378f53c0a6e09548aea083f3ab25e1d94ea1155e29d",

**"time"** : 1388185038,

**"difficulty"** : 1180923195.25802612,

**"nonce"** : 4215469401,

**"tx"** : [

"257e7497fb8bc68421eb2c7b699dbab234831600e7352f0d9e6522c7cf3f6c77",

#[... many more transactions omitted ...]

"05cfd38f6ae6aa83674cc99e4d75a1458c165b7ab84725eda41d018a09176634"

]

}

Looking at this new block, the node finds the previousblockhash field, which contains

the hash of its parent block. It is a hash known to the node, that of the last block on the

chain at height 277,314. Therefore, this new block is a child of the last block on the chain

and extends the existing blockchain. The node adds this new block to the end of the

chain, making the blockchain longer with a new height of 277,315. Figure 7-1 shows

the chain of three blocks, linked by references in the previousblockhash field.

Merkle Trees

Each block in the bitcoin blockchain contains a summary of all the transactions in the

block, using a *merkle tree*.

A *merkle tree*, also known as a *binary hash tree*, is a data structure used for efficiently

summarizing and verifying the integrity of large sets of data. Merkle trees are binary

trees containing cryptographic hashes. The term “tree” is used in computer science to

describe a branching data structure, but these trees are usually displayed upside down

with the “root” at the top and the “leaves” at the bottom of a diagram, as you will see in

the examples that follow.

Merkle trees are used in bitcoin to summarize all the transactions in a block, producing

an overall digital fingerprint of the entire set of transactions, providing a very efficient

process to verify whether a transaction is included in a block. A Merkle tree is constructed

by recursively hashing pairs of nodes until there is only one hash, called the

*root*, or *merkle root*. The cryptographic hash algorithm used in bitcoin’s merkle trees is

SHA256 applied twice, also known as double-SHA256.

When N data elements are hashed and summarized in a merkle tree, you can check to

see if any one data element is included in the tree with at most 2\*log2(N) calculations,

making this a very efficient data structure.

164 | Chapter 7: The Blockchain

*Figure 7-1. Blocks linked in a chain, by reference to the previous block header hash*

Merkle Trees | 165

The merkle tree is constructed bottom-up. In the following example, we start with four

transactions, A, B, C and D, which form the *leaves* of the Merkle tree, as shown in

Figure 7-2. The transactions are not stored in the merkle tree; rather, their data is hashed

and the resulting hash is stored in each leaf node as HA, HB, HC, and HD:

H~A~ = SHA256(SHA256(Transaction A))

Consecutive pairs of leaf nodes are then summarized in a parent node, by concatenating

the two hashes and hashing them together. For example, to construct the parent node

HAB, the two 32-byte hashes of the children are concatenated to create a 64-byte string.

That string is then double-hashed to produce the parent node’s hash:

H~AB~ = SHA256(SHA256(H~A~ + H~B~))

The process continues until there is only one node at the top, the node known as the

Merkle root. That 32-byte hash is stored in the block header and summarizes all the

data in all four transactions.

*Figure 7-2. Calculating the nodes in a merkle tree*

Because the merkle tree is a binary tree, it needs an even number of leaf nodes. If there

is an odd number of transactions to summarize, the last transaction hash will be duplicated

to create an even number of leaf nodes, also known as a *balanced tree*. This is

shown in Figure 7-3, where transaction C is duplicated.

166 | Chapter 7: The Blockchain

*Figure 7-3. Duplicating one data element achieves an even number of data elements*

The same method for constructing a tree from four transactions can be generalized to

construct trees of any size. In bitcoin it is common to have several hundred to more

than a thousand transactions in a single block, which are summarized in exactly the

same way, producing just 32 bytes of data as the single merkle root. In Figure 7-4, you

will see a tree built from 16 transactions. Note that although the root looks bigger than

the leaf nodes in the diagram, it is the exact same size, just 32 bytes. Whether there is

one transaction or a hundred thousand transactions in the block, the merkle root always

summarizes them into 32 bytes.

*Figure 7-4. A merkle tree summarizing many data elements*

To prove that a specific transaction is included in a block, a node only needs to produce

log2(N) 32-byte hashes, constituting an *authentication path* or *merkle path* connecting

Merkle Trees | 167

the specific transaction to the root of the tree. This is especially important as the number

of transactions increases, because the base-2 logarithm of the number of transactions

increases much more slowly. This allows bitcoin nodes to efficiently produce paths of

10 or 12 hashes (320–384 bytes), which can provide proof of a single transaction out of

more than a thousand transactions in a megabyte-size block.

In Figure 7-5, a node can prove that a transaction K is included in the block by producing

a merkle path that is only four 32-byte hashes long (128 bytes total). The path consists

of the four hashes (noted in blue in Figure 7-5) HL, HIJ, HMNOP and HABCDEFGH. With those

four hashes provided as an authentication path, any node can prove that HK (noted in

green in the diagram) is included in the merkle root by computing four additional pairwise

hashes HKL, HIJKL, HIJKLMNOP, and the merkle tree root (outlined in a dotted line in

the diagram).

*Figure 7-5. A merkle path used to prove inclusion of a data element*

The code in Example 7-1 demonstrates the process of creating a merkle tree from the

leaf-node hashes up to the root, using the libbitcoin library for some helper functions.

*Example 7-1. Building a merkle tree*

#include <bitcoin/bitcoin.hpp>

bc::hash\_digest create\_merkle(bc::hash\_digest\_list& merkle)

{

*// Stop if hash list is empty.*

**if** (merkle.empty())

**return** bc::null\_hash;

**else if** (merkle.size() == 1)

**return** merkle[0];

*// While there is more than 1 hash in the list, keep looping...*

**while** (merkle.size() > 1)

{

168 | Chapter 7: The Blockchain

*// If number of hashes is odd, duplicate last hash in the list.*

**if** (merkle.size() % 2 != 0)

merkle.push\_back(merkle.back());

*// List size is now even.*

assert(merkle.size() % 2 == 0);

*// New hash list.*

bc::hash\_digest\_list new\_merkle;

*// Loop through hashes 2 at a time.*

**for** (**auto** it = merkle.begin(); it != merkle.end(); it += 2)

{

*// Join both current hashes together (concatenate).*

bc::data\_chunk concat\_data(bc::hash\_size \* 2);

**auto** concat = bc::make\_serializer(concat\_data.begin());

concat.write\_hash(\*it);

concat.write\_hash(\*(it + 1));

assert(concat.iterator() == concat\_data.end());

*// Hash both of the hashes.*

bc::hash\_digest new\_root = bc::bitcoin\_hash(concat\_data);

*// Add this to the new list.*

new\_merkle.push\_back(new\_root);

}

*// This is the new list.*

merkle = new\_merkle;

*// DEBUG output -------------------------------------*

std::cout << "Current merkle hash list:" << std::endl;

**for** (**const auto**& hash: merkle)

std::cout << " " << bc::encode\_hex(hash) << std::endl;

std::cout << std::endl;

*// --------------------------------------------------*

}

*// Finally we end up with a single item.*

**return** merkle[0];

}

**int** main()

{

*// Replace these hashes with ones from a block to reproduce the same merkle*

*root.*

bc::hash\_digest\_list tx\_hashes{{

bc::de

code\_hash("0000000000000000000000000000000000000000000000000000000000000000"),

bc::de

code\_hash("0000000000000000000000000000000000000000000000000000000000000011"),

bc::de

code\_hash("0000000000000000000000000000000000000000000000000000000000000022"),

}};

**const** bc::hash\_digest merkle\_root = create\_merkle(tx\_hashes);

std::cout << "Result: " << bc::encode\_hex(merkle\_root) << std::endl;

**return** 0;

}

Merkle Trees | 169

Example 7-2 shows the result of compiling and running the merkle code.

*Example 7-2. Compiling and running the merkle example code*

$ *# Compile the merkle.cpp code*

$ g++ -o merkle merkle.cpp **$(**pkg-config --cflags --libs libbitcoin**)**

$ *# Run the merkle executable*

$ ./merkle

Current merkle hash list:

32650049a0418e4380db0af81788635d8b65424d397170b8499cdc28c4d27006

30861db96905c8dc8b99398ca1cd5bd5b84ac3264a4e1b3e65afa1bcee7540c4

Current merkle hash list:

d47780c084bad3830bcdaf6eace035e4c6cbf646d103795d22104fb105014ba3

Result: d47780c084bad3830bcdaf6eace035e4c6cbf646d103795d22104fb105014ba3

The efficiency of merkle trees becomes obvious as the scale increases. Table 7-3 shows

the amount of data that needs to be exchanged as a merkle path to prove that a transaction

is part of a block.

*Table 7-3. Merkle tree efficiency*

Number of transactions Approx. size of block Path size (hashes) Path size (bytes)

16 transactions 4 kilobytes 4 hashes 128 bytes

512 transactions 128 kilobytes 9 hashes 288 bytes

2048 transactions 512 kilobytes 11 hashes 352 bytes

65,535 transactions 16 megabytes 16 hashes 512 bytes

As you can see from the table, while the block size increases rapidly, from 4 KB with 16

transactions to a block size of 16 MB to fit 65,535 transactions, the merkle path required

to prove the inclusion of a transaction increases much more slowly, from 128 bytes to

only 512 bytes. With merkle trees, a node can download just the block headers (80 bytes

per block) and still be able to identify a transaction’s inclusion in a block by retrieving

a small merkle path from a full node, without storing or transmitting the vast majority

of the blockchain, which might be several gigabytes in size. Nodes that do not maintain

a full blockchain, called simplified payment verification (SPV nodes), use merkle paths

to verify transactions without downloading full blocks.

Merkle Trees and Simplified Payment Verification (SPV)

Merkle trees are used extensively by SPV nodes. SPV nodes don’t have all transactions

and do not download full blocks, just block headers. In order to verify that a transaction

is included in a block, without having to download all the transactions in the block, they

use an authentication path, or merkle path.

170 | Chapter 7: The Blockchain

Consider, for example, an SPV node that is interested in incoming payments to an

address contained in its wallet. The SPV node will establish a bloom filter on its connections

to peers to limit the transactions received to only those containing addresses

of interest. When a peer sees a transaction that matches the bloom filter, it will send that

block using a merkleblock message. The merkleblock message contains the block

header as well as a merkle path that links the transaction of interest to the merkle root

in the block. The SPV node can use this merkle path to connect the transaction to the

block and verify that the transaction is included in the block. The SPV node also uses

the block header to link the block to the rest of the blockchain. The combination of

these two links, between the transaction and block, and between the block and blockchain,

proves that the transaction is recorded in the blockchain. All in all, the SPV node

will have received less than a kilobyte of data for the block header and merkle path, an

amount of data that is more than a thousand times less than a full block (about 1 megabyte

currently).

Merkle Trees and Simplified Payment Verification (SPV) | 171

CHAPTER 8

Mining and Consensus

Introduction

Mining is the process by which new bitcoin is added to the money supply. Mining also

serves to secure the bitcoin system against fraudulent transactions or transactions

spending the same amount of bitcoin more than once, known as a double-spend. Miners

provide processing power to the bitcoin network in exchange for the opportunity to be

rewarded bitcoin.

Miners validate new transactions and record them on the global ledger. A new block,

containing transactions that occurred since the last block, is “mined” every 10 minutes,

thereby adding those transactions to the blockchain. Transactions that become part of

a block and added to the blockchain are considered “confirmed,” which allows the new

owners of bitcoin to spend the bitcoin they received in those transactions.

Miners receive two types of rewards for mining: new coins created with each new block,

and transaction fees from all the transactions included in the block. To earn this reward,

the miners compete to solve a difficult mathematical problem based on a cryptographic

hash algorithm. The solution to the problem, called the proof of work, is included in

the new block and acts as proof that the miner expended significant computing effort.

The competition to solve the proof-of-work algorithm to earn reward and the right to

record transactions on the blockchain is the basis for bitcoin’s security model.

The process of new coin generation is called mining because the reward is designed to

simulate diminishing returns, just like mining for precious metals. Bitcoin’s money

supply is created through mining, similar to how a central bank issues new money by

printing bank notes. The amount of newly created bitcoin a miner can add to a block

decreases approximately every four years (or precisely every 210,000 blocks). It started

at 50 bitcoin per block in January of 2009 and halved to 25 bitcoin per block in November

of 2012. It will halve again to 12.5 bitcoin per block sometime in 2016. Based on this

formula, bitcoin mining rewards decrease exponentially until approximately the year

173

2140, when all bitcoin (20.99999998 million) will have been issued. After 2140, no new

bitcoins will be issued.

Bitcoin miners also earn fees from transactions. Every transaction may include a transaction

fee, in the form of a surplus of bitcoin between the transaction’s inputs and outputs.

The winning bitcoin miner gets to “keep the change” on the transactions included

in the winning block. Today, the fees represent 0.5% or less of a bitcoin miner’s income,

the vast majority coming from the newly minted bitcoins. However, as the reward decreases

over time and the number of transactions per block increases, a greater proportion

of bitcoin mining earnings will come from fees. After 2140, all bitcoin miner

earnings will be in the form of transaction fees.

The word “mining” is somewhat misleading. By evoking the extraction of precious

metals, it focuses our attention on the reward for mining, the new bitcoins in each block.

Although mining is incentivized by this reward, the primary purpose of mining is not

the reward or the generation of new coins. If you view mining only as the process by

which coins are created, you are mistaking the means (incentives) as a goal of the process.

Mining is the main process of the decentralized clearinghouse, by which transactions

are validated and cleared. Mining secures the bitcoin system and enables the

emergence of network-wide consensus without a central authority.

Mining is the invention that makes bitcoin special, a decentralized security mechanism

that is the basis for peer-to-peer digital cash. The reward of newly minted coins and

transaction fees is an incentive scheme that aligns the actions of miners with the security

of the network, while simultaneously implementing the monetary supply.

In this chapter, we will first examine mining as a monetary supply mechanism and then

look at the most important function of mining: the decentralized emergent consensus

mechanism that underpins bitcoin’s security.

Bitcoin Economics and Currency Creation

Bitcoins are “minted” during the creation of each block at a fixed and diminishing rate.

Each block, generated on average every 10 minutes, contains entirely new bitcoins,

created from nothing. Every 210,000 blocks, or approximately every four years, the

currency issuance rate is decreased by 50%. For the first four years of operation of the

network, each block contained 50 new bitcoins.

In November 2012, the new bitcoin issuance rate was decreased to 25 bitcoins per block

and it will decrease again to 12.5 bitcoins at block 420,000, which will be mined sometime

in 2016. The rate of new coins decreases like this exponentially over 64 “halvings”

until block 13,230,000 (mined approximately in year 2137), when it reaches the minimum

currency unit of 1 satoshi. Finally, after 13.44 million blocks, in approximately

2140, all 2,099,999,997,690,000 satoshis, or almost 21 million bitcoins, will be issued.

Thereafter, blocks will contain no new bitcoins, and miners will be rewarded solely

174 | Chapter 8: Mining and Consensus

through the transaction fees. Figure 8-1 shows the total bitcoin in circulation over time,

as the issuance of currency decreases.

In the example code in Example 8-1, we calculate the total amount of bitcoin that will

be issued.

*Example 8-1. A script for calculating how much total bitcoin will be issued*

*# Original block reward for miners was 50 BTC*

start\_block\_reward = 50

*# 210000 is around every 4 years with a 10 minute block interval*

reward\_interval = 210000

**def** max\_money():

*# 50 BTC = 50 0000 0000 Satoshis*

current\_reward = 50 \* 10\*\*8

total = 0

**while** current\_reward > 0:

total += reward\_interval \* current\_reward

current\_reward /= 2

**return** total

**print** "Total BTC to ever be created:", max\_money(), "Satoshis"

Example 8-2 shows the output produced by running this script.

*Example 8-2. Running the max\_money.py script*

$ python max\_money.py

Total BTC to ever be created: 2099999997690000 Satoshis

*Figure 8-1. Supply of bitcoin currency over time based on a geometrically decreasing*

*issuance rate*

Introduction | 175

The finite and diminishing issuance creates a fixed monetary supply that resists inflation.

Unlike a fiat currency, which can be printed in infinite numbers by a central bank,

bitcoin can never be inflated by printing.

Deflationary Money

The most important and debated consequence of a fixed and diminishing monetary

issuance is that the currency will tend to be inherently *deflationary*. Deflation is the

phenomenon of appreciation of value due to a mismatch in supply and demand that

drives up the value (and exchange rate) of a currency. The opposite of inflation, price

deflation means that the money has more purchasing power over time.

Many economists argue that a deflationary economy is a disaster that should be avoided

at all costs. That is because in a period of rapid deflation, people tend to hoard money

instead of spending it, hoping that prices will fall. Such a phenomenon unfolded during

Japan’s “Lost Decade,” when a complete collapse of demand pushed the currency into a

deflationary spiral.

Bitcoin experts argue that deflation is not bad per se. Rather, deflation is associated with

a collapse in demand because that is the only example of deflation we have to study. In

a fiat currency with the possibility of unlimited printing, it is very difficult to enter a

deflationary spiral unless there is a complete collapse in demand and an unwillingness

to print money. Deflation in bitcoin is not caused by a collapse in demand, but by a

predictably constrained supply.

In practice, it has become evident that the hoarding instinct caused by a deflationary

currency can be overcome by discounting from vendors, until the discount overcomes

the hoarding instinct of the buyer. Because the seller is also motivated to hoard, the

discount becomes the equilibrium price at which the two hoarding instincts are matched.

With discounts of 30% on the bitcoin price, most bitcoin retailers are not experiencing

difficulty overcoming the hoarding instinct and generating revenue. It remains

to be seen whether the deflationary aspect of the currency is really a problem when it is

not driven by rapid economic retraction.

Decentralized Consensus

In the previous chapter we looked at the blockchain, the global public ledger (list) of all

transactions, which everyone in the bitcoin network accepts as the authoritative record

of ownership.

But how can everyone in the network agree on a single universal “truth” about who

owns what, without having to trust anyone? All traditional payment systems depend on

a trust model that has a central authority providing a clearinghouse service, basically

verifying and clearing all transactions. Bitcoin has no central authority, yet somehow

176 | Chapter 8: Mining and Consensus

every full node has a complete copy of a public ledger that it can trust as the authoritative

record. The blockchain is not created by a central authority, but is assembled independently

by every node in the network. Somehow, every node in the network, acting

on information transmitted across insecure network connections, can arrive at the same

conclusion and assemble a copy of the same public ledger as everyone else. This chapter

examines the process by which the bitcoin network achieves global consensus without

central authority.

Satoshi Nakamoto’s main invention is the decentralized mechanism for *emergent consensus*.

Emergent, because consensus is not achieved explicitly—there is no election or

fixed moment when consensus occurs. Instead, consensus is an emergent artifact of the

asynchronous interaction of thousands of independent nodes, all following simple rules.

All the properties of bitcoin, including currency, transactions, payments, and the security

model that does not depend on central authority or trust, derive from this invention.

Bitcoin’s decentralized consensus emerges from the interplay of four processes that occur

independently on nodes across the network:

• Independent verification of each transaction, by every full node, based on a comprehensive

list of criteria

• Independent aggregation of those transactions into new blocks by mining nodes,

coupled with demonstrated computation through a proof-of-work algorithm

• Independent verification of the new blocks by every node and assembly into a chain

• Independent selection, by every node, of the chain with the most cumulative computation

demonstrated through proof of work

In the next few sections we will examine these processes and how they interact to create

the emergent property of network-wide consensus that allows any bitcoin node to assemble

its own copy of the authoritative, trusted, public, global ledger.

Independent Verification of Transactions

In Chapter 5, we saw how wallet software creates transactions by collecting UTXO,

providing the appropriate unlocking scripts, and then constructing new outputs assigned

to a new owner. The resulting transaction is then sent to the neighboring nodes

in the bitcoin network so that it can be propagated across the entire bitcoin network.

However, before forwarding transactions to its neighbors, every bitcoin node that receives

a transaction will first verify the transaction. This ensures that only valid transactions

are propagated across the network, while invalid transactions are discarded at

the first node that encounters them.

Each node verifies every transaction against a long checklist of criteria:

Independent Verification of Transactions | 177

• The transaction’s syntax and data structure must be correct.

• Neither lists of inputs or outputs are empty.

• The transaction size in bytes is less than MAX\_BLOCK\_SIZE.

• Each output value, as well as the total, must be within the allowed range of values

(less than 21m coins, more than 0).

• None of the inputs have hash=0, N=–1 (coinbase transactions should not be relayed).

• nLockTime is less than or equal to INT\_MAX.

• The transaction size in bytes is greater than or equal to 100.

• The number of signature operations contained in the transaction is less than the

signature operation limit.

• The unlocking script (scriptSig) can only push numbers on the stack, and the

locking script (scriptPubkey) must match isStandard forms (this rejects “nonstandard”

transactions).

• A matching transaction in the pool, or in a block in the main branch, must exist.

• For each input, if the referenced output exists in any other transaction in the pool,

the transaction must be rejected.

• For each input, look in the main branch and the transaction pool to find the referenced

output transaction. If the output transaction is missing for any input, this

will be an orphan transaction. Add to the orphan transactions pool, if a matching

transaction is not already in the pool.

• For each input, if the referenced output transaction is a coinbase output, it must

have at least COINBASE\_MATURITY (100) confirmations.

• For each input, the referenced output must exist and cannot already be spent.

• Using the referenced output transactions to get input values, check that each input

value, as well as the sum, are in the allowed range of values (less than 21m coins,

more than 0).

• Reject if the sum of input values is less than sum of output values.

• Reject if transaction fee would be too low to get into an empty block.

• The unlocking scripts for each input must validate against the corresponding output

locking scripts.

These conditions can be seen in detail in the functions AcceptToMemoryPool, Check

Transaction, and CheckInputs in the bitcoin reference client. Note that the conditions

change over time, to address new types of denial-of-service attacks or sometimes to

relax the rules so as to include more types of transactions.

178 | Chapter 8: Mining and Consensus

By independently verifying each transaction as it is received and before propagating it,

every node builds a pool of valid new transactions (the transaction pool), roughly in

the same order.

Mining Nodes

Some of the nodes on the bitcoin network are specialized nodes called *miners*. In Chapter

1 we introduced Jing, a computer engineering student in Shanghai, China, who is a

bitcoin miner. Jing earns bitcoin by running a “mining rig,” which is a specialized

computer-hardware system designed to mine bitcoins. Jing’s specialized mining hardware

is connected to a server running a full bitcoin node. Unlike Jing, some miners mine

without a full node, as we will see in “Mining Pools” on page 207. Like every other full

node, Jing’s node receives and propagates unconfirmed transactions on the bitcoin network.

Jing’s node, however, also aggregates these transactions into new blocks.

Jing’s node is listening for new blocks, propagated on the bitcoin network, as do all

nodes. However, the arrival of a new block has special significance for a mining node.

The competition among miners effectively ends with the propagation of a new block

that acts as an announcement of a winner. To miners, receiving a new block means

someone else won the competition and they lost. However, the end of one round of a

competition is also the beginning of the next round. The new block is not just a checkered

flag, marking the end of the race; it is also the starting pistol in the race for the next

block.

Aggregating Transactions into Blocks

After validating transactions, a bitcoin node will add them to the *memory pool*, or

*transaction pool*, where transactions await until they can be included (mined) into a

block. Jing’s node collects, validates, and relays new transactions just like any other node.

Unlike other nodes, however, Jing’s node will then aggregate these transactions into a

*candidate block*.

Let’s follow the blocks that were created during the time Alice bought a cup of coffee

from Bob’s Cafe (see “Buying a Cup of Coffee” on page 16). Alice’s transaction was

included in block 277,316. For the purpose of demonstrating the concepts in this chapter,

let’s assume that block was mined by Jing’s mining system and follow Alice’s transaction

as it becomes part of this new block.

Jing’s mining node maintains a local copy of the blockchain, the list of all blocks created

since the beginning of the bitcoin system in 2009. By the time Alice buys the cup of

coffee, Jing’s node has assembled a chain up to block 277,314. Jing’s node is listening for

transactions, trying to mine a new block and also listening for blocks discovered by

other nodes. As Jing’s node is mining, it receives block 277,315 through the bitcoin

Mining Nodes | 179

network. The arrival of this block signifies the end of the competition for block 277,315

and the beginning of the competition to create block 277,316.

During the previous 10 minutes, while Jing’s node was searching for a solution to block

277,315, it was also collecting transactions in preparation for the next block. By now it

has collected a few hundred transactions in the memory pool. Upon receiving block

277,315 and validating it, Jing’s node will also check all the transactions in the memory

pool and remove any that were included in block 277,315. Whatever transactions remain

in the memory pool are unconfirmed and are waiting to be recorded in a new block.

Jing’s node immediately constructs a new empty block, a candidate for block 277,316.

This block is called a candidate block because it is not yet a valid block, as it does not

contain a valid proof of work. The block becomes valid only if the miner succeeds in

finding a solution to the proof-of-work algorithm.

Transaction Age, Fees, and Priority

To construct the candidate block, Jing’s bitcoin node selects transactions from the

memory pool by applying a priority metric to each transaction and adding the highest

priority transactions first. Transactions are prioritized based on the “age” of the UTXO

that is being spent in their inputs, allowing for old and high-value inputs to be prioritized

over newer and smaller inputs. Prioritized transactions can be sent without any fees, if

there is enough space in the block.

The priority of a transaction is calculated as the sum of the value and age of the inputs

divided by the total size of the transaction:

Priority = Sum (Value of input \* Input Age) / Transaction Size

In this equation, the value of an input is measured in the base unit, satoshis (1/100m of

a bitcoin). The age of a UTXO is the number of blocks that have elapsed since the UTXO

was recorded on the blockchain, measuring how many blocks “deep” into the blockchain

it is. The size of the transaction is measured in bytes.

For a transaction to be considered “high priority,” its priority must be greater than

57,600,000, which corresponds to one bitcoin (100m satoshis), aged one day (144

blocks), in a transaction of 250 bytes total size:

High Priority > 100,000,000 satoshis \* 144 blocks / 250 bytes = 57,600,000

The first 50 kilobytes of transaction space in a block are set aside for high-priority

transactions. Jing’s node will fill the first 50 kilobytes, prioritizing the highest priority

transactions first, regardless of fee. This allows high-priority transactions to be processed

even if they carry zero fees.

Jing’s mining node then fills the rest of the block up to the maximum block size

(MAX\_BLOCK\_SIZE in the code), with transactions that carry at least the minimum fee,

prioritizing those with the highest fee per kilobyte of transaction.

180 | Chapter 8: Mining and Consensus

If there is any space remaining in the block, Jing’s mining node might choose to fill it

with no-fee transactions. Some miners choose to mine transactions without fees on a

best-effort basis. Other miners may choose to ignore transactions without fees.

Any transactions left in the memory pool, after the block is filled, will remain in the

pool for inclusion in the next block. As transactions remain in the memory pool, their

inputs “age,” as the UTXO they spend get deeper into the blockchain with new blocks

added on top. Because a transaction’s priority depends on the age of its inputs, transactions

remaining in the pool will age and therefore increase in priority. Eventually a

transaction without fees might reach a high enough priority to be included in the block

for free.

Bitcoin transactions do not have an expiration time-out. A transaction that is valid now

will be valid in perpetuity. However, if a transaction is only propagated across the network

once, it will persist only as long as it is held in a mining node memory pool. When

a mining node is restarted, its memory pool is wiped clear, because it is a transient nonpersistent

form of storage. Although a valid transaction might have been propagated

across the network, if it is not executed it may eventually not reside in the memory pool

of any miner. Wallet software is expected to retransmit such transactions or reconstruct

them with higher fees if they are not successfully executed within a reasonable amount

of time.

When Jing’s node aggregates all the transactions from the memory pool, the new candidate

block has 418 transactions with total transaction fees of 0.09094928 bitcoin. You

can see this block in the blockchain using the Bitcoin Core client command-line interface,

as shown in Example 8-3.

$ bitcoin-cli getblockhash

2773160000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4

$ bitcoin-cli getblock

0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4

*Example 8-3. Block 277,316*

{

**"hash"** : "0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4",

**"confirmations"** : 35561,

**"size"** : 218629,

**"height"** : 277316,

**"version"** : 2,

**"merkleroot"** :

"c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e",

**"tx"** : [

"d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",

"b268b45c59b39d759614757718b9918caf0ba9d97c56f3b91956ff877c503fbe",

... 417 more transactions ...

Aggregating Transactions into Blocks | 181

],

**"time"** : 1388185914,

**"nonce"** : 924591752,

**"bits"** : "1903a30c",

**"difficulty"** : 1180923195.25802612,

**"chainwork"** :

"000000000000000000000000000000000000000000000934695e92aaf53afa1a",

**"previousblockhash"** :

"0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569",

**"nextblockhash"** :

"000000000000000010236c269dd6ed714dd5db39d36b33959079d78dfd431ba7"

}

The Generation Transaction

The first transaction added to the block is a special transaction, called a *generation*

*transaction* or *coinbase transaction*. This transaction is constructed by Jing’s node and

is his reward for the mining effort. Jing’s node creates the generation transaction as a

payment to his own wallet: “Pay Jing’s address 25.09094928 bitcoin.” The total amount

of reward that Jing collects for mining a block is the sum of the coinbase reward (25

new bitcoins) and the transaction fees (0.09094928) from all the transactions included

in the block as shown in Example 8-4:

$ bitcoin-cli getrawtransaction

d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f 1

*Example 8-4. Generation transaction*

{

**"hex"** :

"01000000010000000000000000000000000000000000000000000000000000000000000000ffffffff0

f03443b0403858402062f503253482fffffffff0110c08d9500000000232102aa970c592640d19de03ff

6f329d6fd2eecb023263b9ba5d1b81c29b523da8b21ac00000000",

**"txid"** : "d5ada064c6417ca25c4308bd158c34b77e1c0eca2a73cda16c737e7424afba2f",

**"version"** : 1,

**"locktime"** : 0,

**"vin"** : [

{

**"coinbase"** : "03443b0403858402062f503253482f",

**"sequence"** : 4294967295

}

],

**"vout"** : [

{

**"value"** : 25.09094928,

**"n"** : 0,

**"scriptPubKey"** : {

**"asm"** :

"02aa970c592640d19de03ff6f329d6fd2eecb023263b9ba5d1b81c29b523da8b21OP\_CHECKSIG",

**"hex"** :

"2102aa970c592640d19de03ff6f329d6fd2eecb023263b9ba5d1b81c29b523da8b21ac",

182 | Chapter 8: Mining and Consensus

**"reqSigs"** : 1,

**"type"** : "pubkey",

**"addresses"** : [

"1MxTkeEP2PmHSMze5tUZ1hAV3YTKu2Gh1N"

]

}

}

],

**"blockhash"** :

"0000000000000001b6b9a13b095e96db41c4a928b97ef2d944a9b31b2cc7bdc4",

**"confirmations"** : 35566,

**"time"** : 1388185914,

**"blocktime"** : 1388185914

}

Unlike regular transactions, the generation transaction does not consume (spend) UTXO

as inputs. Instead, it has only one input, called the *coinbase*, which creates bitcoin

from nothing. The generation transaction has one output, payable to the miner’s own

bitcoin address. The output of the generation transaction sends the value of 25.09094928

bitcoins to the miner’s bitcoin address, in this case 1MxTkeEP2PmHSMze5tUZ1hAV3YT

Ku2Gh1N.

Coinbase Reward and Fees

To construct the generation transaction, Jing’s node first calculates the total amount of

transaction fees by adding all the inputs and outputs of the 418 transactions that were

added to the block. The fees are calculated as:

Total Fees = Sum(Inputs) - Sum(Outputs)

In block 277,316, the total transaction fees are 0.09094928 bitcoins.

Next, Jing’s node calculates the correct reward for the new block. The reward is calculated

based on the block height, starting at 50 bitcoins per block and reduced by half

every 210,000 blocks. Because this block is at height 277,316, the correct reward is 25

bitcoins.

The calculation can be seen in function GetBlockValue in the Bitcoin Core client, as

shown in Example 8-5.

*Example 8-5. Calculating the block reward—Function GetBlockValue, Bitcoin Core*

*Client, main.cpp, line 1305*

**int64\_t** GetBlockValue(**int** nHeight, **int64\_t** nFees)

{

**int64\_t** nSubsidy = 50 \* COIN;

**int** halvings = nHeight / Params().SubsidyHalvingInterval();

*// Force block reward to zero when right shift is undefined.*

**if** (halvings >= 64)

Aggregating Transactions into Blocks | 183

**return** nFees;

*// Subsidy is cut in half every 210,000 blocks which will occur approximately*

*every 4 years.*

nSubsidy >>= halvings;

**return** nSubsidy + nFees;

}

The initial subsidy is calculated in satoshis by multiplying 50 with the COIN constant

(100,000,000 satoshis). This sets the initial reward (nSubsidy) at 5 billion satoshis.

Next, the function calculates the number of halvings that have occurred by dividing

the current block height by the halving interval (SubsidyHalvingInterval). In the case

of block 277,316, with a halving interval every 210,000 blocks, the result is 1 halving.

The maximum number of halvings allowed is 64, so the code imposes a zero reward

(return only the fees) if the 64 halvings is exceeded.

Next, the function uses the binary-right-shift operator to divide the reward (nSubsi

dy) by two for each round of halving. In the case of block 277,316, this would binaryright-

shift the reward of 5 billion satoshis once (one halving) and result in 2.5 billion

satoshis, or 25 bitcoins. The binary-right-shift operator is used because it is more efficient

for division by two than integer or floating-point division.

Finally, the coinbase reward (nSubsidy) is added to the transaction fees (nFees), and

the sum is returned.

Structure of the Generation Transaction

With these calculations, Jing’s node then constructs the generation transaction to pay

himself 25.09094928 bitcoin.

As you can see in Example 8-4, the generation transaction has a special format. Instead

of a transaction input specifying a previous UTXO to spend, it has a “coinbase” input.

We examined transaction inputs in Table 5-3. Let’s compare a regular transaction input

with a generation transaction input. Table 8-1 shows the structure of a regular transaction,

while Table 8-2 shows the structure of the generation transaction’s input.

*Table 8-1. The structure of a “normal” transaction input*

Size Field Description

32 bytes Transaction Hash Pointer to the transaction containing the UTXO to be spent

4 bytes Output Index The index number of the UTXO to be spent, first one is 0

1-9 bytes (VarInt) Unlocking-Script Size Unlocking-Script length in bytes, to follow

Variable Unlocking-Script A script that fulfills the conditions of the UTXO locking script.

4 bytes Sequence Number Currently disabled Tx-replacement feature, set to 0xFFFFFFFF

184 | Chapter 8: Mining and Consensus

*Table 8-2. The structure of a generation transaction input*

Size Field Description

32 bytes Transaction Hash All bits are zero: Not a transaction hash reference

4 bytes Output Index All bits are ones: 0xFFFFFFFF

1-9 bytes (VarInt) Coinbase Data Size Length of the coinbase data, from 2 to 100 bytes

Variable Coinbase Data Arbitrary data used for extra nonce and mining tags in v2 blocks, must begin with block

height

4 bytes Sequence Number Set to 0xFFFFFFFF

In a generation transaction, the first two fields are set to values that do not represent a

UTXO reference. Instead of a “Transaction Hash,” the first field is filled with 32 bytes

all set to zero. The “Output Index” is filled with 4 bytes all set to 0xFF (255 decimal).

The “Unlocking Script” is replaced by coinbase data, an arbitrary data field used by the

miners.

Coinbase Data

Generation transactions do not have an unlocking script (a.k.a., scriptSig) field. Instead,

this field is replaced by coinbase data, which must be between 2 and 100 bytes.

Except for the first few bytes, the rest of the coinbase data can be used by miners in any

way they want; it is arbitrary data.

In the genesis block, for example, Satoshi Nakamoto added the text “The Times 03/Jan/

2009 Chancellor on brink of second bailout for banks” in the coinbase data, using it as

a proof of the date and to convey a message. Currently, miners use the coinbase data to

include extra nonce values and strings identifying the mining pool, as we will see in the

following sections.

The first few bytes of the coinbase used to be arbitrary, but that is no longer the case.

As per Bitcoin Improvement Proposal 34 (BIP0034), version-2 blocks (blocks with the

version field set to 2) must contain the block height index as a script “push” operation

in the beginning of the coinbase field.

In block 277,316 we see that the coinbase (see Example 8-4), which is in the “Unlocking

Script” or scriptSig field of the transaction input, contains the hexadecimal value

03443b0403858402062f503253482f. Let’s decode this value.

The first byte, 03, instructs the script execution engine to push the next three bytes onto

the script stack (see Table A-1). The next three bytes, 0x443b04, are the block height

encoded in little-endian format (backward, least significant byte first). Reverse the order

of the bytes and the result is 0x043b44, which is 277,316 in decimal.

Aggregating Transactions into Blocks | 185

The next few hexadecimal digits (03858402062) are used to encode an extra *nonce* (see

“The Extra Nonce Solution” on page 206), or random value, used to find a suitable proof

of work solution.

The final part of the coinbase data (2f503253482f) is the ASCII-encoded string /

P2SH/, which indicates that the mining node that mined this block supports the pay-toscript-

hash (P2SH) improvement defined in BIP0016. The introduction of the P2SH

capability required a “vote” by miners to endorse either BIP0016 or BIP0017. Those

endorsing the BIP0016 implementation were to include /P2SH/ in their coinbase data.

Those endorsing the BIP0017 implementation of P2SH were to include the string p2sh/

CHV in their coinbase data. The BIP0016 was elected as the winner, and many miners

continued including the string /P2SH/ in their coinbase to indicate support for this

feature.

Example 8-6 uses the libbitcoin library introduced in “Alternative Clients, Libraries, and

Toolkits” on page 56 to extract the coinbase data from the genesis block, displaying

Satoshi’s message. Note that the libbitcoin library contains a static copy of the genesis

block, so the example code can retrieve the genesis block directly from the library.

*Example 8-6. Extract the coinbase data from the genesis block*

*/\**

*Display the genesis block message by Satoshi.*

*\*/*

#include <iostream>

#include <bitcoin/bitcoin.hpp>

**int** main()

{

*// Create genesis block.*

bc::block\_type block = bc::genesis\_block();

*// Genesis block contains a single coinbase transaction.*

assert(block.transactions.size() == 1);

*// Get first transaction in block (coinbase).*

**const** bc::transaction\_type& coinbase\_tx = block.transactions[0];

*// Coinbase tx has a single input.*

assert(coinbase\_tx.inputs.size() == 1);

**const** bc::transaction\_input\_type& coinbase\_input = coinbase\_tx.inputs[0];

*// Convert the input script to its raw format.*

**const** bc::data\_chunk& raw\_message = save\_script(coinbase\_input.script);

*// Convert this to an std::string.*

std::string message;

message.resize(raw\_message.size());

std::copy(raw\_message.begin(), raw\_message.end(), message.begin());

*// Display the genesis block message.*

std::cout << message << std::endl;

**return** 0;

}

186 | Chapter 8: Mining and Consensus

We compile the code with the GNU C++ compiler and run the resulting executable, as

shown in Example 8-7.

*Example 8-7. Compiling and running the satoshi-words example code*

$ *# Compile the code*

$ g++ -o satoshi-words satoshi-words.cpp **$(**pkg-config --cflags --libs libbitcoin**)**

$ *# Run the executable*

$ ./satoshi-words

^DII<GS>^A^DEThe Times 03/Jan/2009 Chancellor on brink of second bailout **for** banks

Constructing the Block Header

To construct the block header, the mining node needs to fill in six fields, as listed in

Table 8-3.

*Table 8-3. The structure of the block header*

Size Field Description

4 bytes Version A version number to track software/protocol upgrades

32 bytes Previous Block Hash A reference to the hash of the previous (parent) block in the chain

32 bytes Merkle Root A hash of the root of the merkle tree of this block’s transactions

4 bytes Timestamp The approximate creation time of this block (seconds from Unix Epoch)

4 bytes Difficulty Target The proof-of-work algorithm difficulty target for this block

4 bytes Nonce A counter used for the proof-of-work algorithm

At the time that block 277,316 was mined, the version number describing the block

structure is version 2, which is encoded in little-endian format in 4 bytes as 0x02000000.

Next, the mining node needs to add the “Previous Block Hash.” That is the hash of the

block header of block 277,315, the previous block received from the network, which

Jing’s node has accepted and selected as the parent of the candidate block 277,316. The

block header hash for block 277,315 is:

0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569

The next step is to summarize all the transactions with a merkle tree, in order to add

the merkle root to the block header. The generation transaction is listed as the first

transaction in the block. Then, 418 more transactions are added after it, for a total of

419 transactions in the block. As we saw in the “Merkle Trees” on page 164, there must

be an even number of “leaf ” nodes in the tree, so the last transaction is duplicated,

creating 420 nodes, each containing the hash of one transaction. The transaction hashes

are then combined, in pairs, creating each level of the tree, until all the transactions are

summarized into one node at the “root” of the tree. The root of the merkle tree summarizes

all the transactions into a single 32-byte value, which you can see listed as

“merkle root” in Example 8-3, and here:

Constructing the Block Header | 187

c91c008c26e50763e9f548bb8b2fc323735f73577effbc55502c51eb4cc7cf2e

The mining node will then add a 4-byte timestamp, encoded as a Unix “Epoch” timestamp,

which is based on the number of seconds elapsed from January 1, 1970, midnight

UTC/GMT. The time 1388185914 is equal to Friday, 27 Dec 2013, 23:11:54 UTC/GMT.

The node then fills in the difficulty target, which defines the required proof-of-work

difficulty to make this a valid block. The difficulty is stored in the block as a “difficulty

bits” metric, which is a mantissa-exponent encoding of the target. The encoding has a

1-byte exponent, followed by a 3-byte mantissa (coefficient). In block 277,316, for example,

the difficulty bits value is 0x1903a30c. The first part 0x19 is a hexadecimal exponent,

while the next part, 0x03a30c, is the coefficient. The concept of a difficulty target

is explained in “Difficulty Target and Retargeting” on page 195 and the “difficulty bits”

representation is explained in “Difficulty Representation” on page 194.

The final field is the nonce, which is initialized to zero.

With all the other fields filled, the block header is now complete and the process of

mining can begin. The goal is now to find a value for the nonce that results in a block

header hash that is less than the difficulty target. The mining node will need to test

billions or trillions of nonce values before a nonce is found that satisfies the requirement.

Mining the Block

Now that a candidate block has been constructed by Jing’s node, it is time for Jing’s

hardware mining rig to “mine” the block, to find a solution to the proof-of-work algorithm

that makes the block valid. Throughout this book we have studied cryptographic

hash functions as used in various aspects of the bitcoin system. The hash function

SHA256 is the function used in bitcoin’s mining process.

In the simplest terms, mining is the process of hashing the block header repeatedly,

changing one parameter, until the resulting hash matches a specific target. The hash

function’s result cannot be determined in advance, nor can a pattern be created that will

produce a specific hash value. This feature of hash functions means that the only way

to produce a hash result matching a specific target is to try again and again, randomly

modifying the input until the desired hash result appears by chance.

Proof-Of-Work Algorithm

A hash algorithm takes an arbitrary-length data input and produces a fixed-length deterministic

result, a digital fingerprint of the input. For any specific input, the resulting

hash will always be the same and can be easily calculated and verified by anyone implementing

the same hash algorithm. The key characteristic of a cryptographic hash

algorithm is that it is virtually impossible to find two different inputs that produce the

188 | Chapter 8: Mining and Consensus

same fingerprint. As a corollary, it is also virtually impossible to select an input in such

a way as to produce a desired fingerprint, other than trying random inputs.

With SHA256, the output is always 256 bits long, regardless of the size of the input. In

Example 8-8, we will use the Python interpreter to calculate the SHA256 hash of the

phrase, “I am Satoshi Nakamoto.”

*Example 8-8. SHA256 example*

$ python

Python 2.7.1

**>>> import hashlib**

**>>> print** hashlib.sha256("I am Satoshi Nakamoto").hexdigest()

5d7c7ba21cbbcd75d14800b100252d5b428e5b1213d27c385bc141ca6b47989e

Example 8-8 shows the result of calculating the hash of "I am Satoshi Nakamoto":

5d7c7ba21cbbcd75d14800b100252d5b428e5b1213d27c385bc141ca6b47989e. This

256-bit number is the *hash* or *digest* of the phrase and depends on every part of the

phrase. Adding a single letter, punctuation mark, or any other character will produce a

different hash.

Now, if we change the phrase, we should expect to see completely different hashes. Let’s

try that by adding a number to the end of our phrase, using the simple Python scripting

in Example 8-9.

*Example 8-9. SHA256 A script for generating many hashes by iterating on a nonce*

*# example of iterating a nonce in a hashing algorithm's input*

**import hashlib**

text = "I am Satoshi Nakamoto"

*# iterate nonce from 0 to 19*

**for** nonce **in** xrange(20):

*# add the nonce to the end of the text*

input = text + str(nonce)

*# calculate the SHA-256 hash of the input (text+nonce)*

hash = hashlib.sha256(input).hexdigest()

*# show the input and hash result*

**print** input, '=>', hash

Running this will produce the hashes of several phrases, made different by adding a

number at the end of the text. By incrementing the number, we can get different hashes,

as shown in Example 8-10.

Mining the Block | 189

*Example 8-10. SHA256 output of a script for generating many hashes by iterating on a*

*nonce*

$ python hash\_example.py

I am Satoshi Nakamoto0 => a80a81401765c8eddee25df36728d732...

I am Satoshi Nakamoto1 => f7bc9a6304a4647bb41241a677b5345f...

I am Satoshi Nakamoto2 => ea758a8134b115298a1583ffb80ae629...

I am Satoshi Nakamoto3 => bfa9779618ff072c903d773de30c99bd...

I am Satoshi Nakamoto4 => bce8564de9a83c18c31944a66bde992f...

I am Satoshi Nakamoto5 => eb362c3cf3479be0a97a20163589038e...

I am Satoshi Nakamoto6 => 4a2fd48e3be420d0d28e202360cfbaba...

I am Satoshi Nakamoto7 => 790b5a1349a5f2b909bf74d0d166b17a...

I am Satoshi Nakamoto8 => 702c45e5b15aa54b625d68dd947f1597...

I am Satoshi Nakamoto9 => 7007cf7dd40f5e933cd89fff5b791ff0...

I am Satoshi Nakamoto10 => c2f38c81992f4614206a21537bd634a...

I am Satoshi Nakamoto11 => 7045da6ed8a914690f087690e1e8d66...

I am Satoshi Nakamoto12 => 60f01db30c1a0d4cbce2b4b22e88b9b...

I am Satoshi Nakamoto13 => 0ebc56d59a34f5082aaef3d66b37a66...

I am Satoshi Nakamoto14 => 27ead1ca85da66981fd9da01a8c6816...

I am Satoshi Nakamoto15 => 394809fb809c5f83ce97ab554a2812c...

I am Satoshi Nakamoto16 => 8fa4992219df33f50834465d3047429...

I am Satoshi Nakamoto17 => dca9b8b4f8d8e1521fa4eaa46f4f0cd...

I am Satoshi Nakamoto18 => 9989a401b2a3a318b01e9ca9a22b0f3...

I am Satoshi Nakamoto19 => cda56022ecb5b67b2bc93a2d764e75f...

Each phrase produces a completely different hash result. They seem completely random,

but you can reproduce the exact results in this example on any computer with Python

and see the same exact hashes.

The number used as a variable in such a scenario is called a *nonce*. The nonce is used

to vary the output of a cryptographic function, in this case to vary the SHA256 fingerprint

of the phrase.

To make a challenge out of this algorithm, let’s set an arbitrary target: find a phrase that

produces a hexadecimal hash that starts with a zero. Fortunately, this isn’t difficult!

Example 8-10 shows that the phrase “I am Satoshi Nakamoto13” produces the hash

0ebc56d59a34f5082aaef3d66b37a661696c2b618e62432727216ba9531041a5, which

fits our criteria. It took 13 attempts to find it. In terms of probabilities, if the output of

the hash function is evenly distributed we would expect to find a result with a 0 as the

hexadecimal prefix once every 16 hashes (one out of 16 hexadecimal digits 0 through

F). In numerical terms, that means finding a hash value that is less than

0x1000000000000000000000000000000000000000000000000000000000000000. We

call this threshold the *target* and the goal is to find a hash that is numerically *less than*

*the target*. If we decrease the target, the task of finding a hash that is less than the target

becomes more and more difficult.

190 | Chapter 8: Mining and Consensus

To give a simple analogy, imagine a game where players throw a pair of dice repeatedly,

trying to throw less than a specified target. In the first round, the target is 12. Unless

you throw double-six, you win. In the next round the target is 11. Players must throw

10 or less to win, again an easy task. Let’s say a few rounds later the target is down to 5.

Now, more than half the dice throws will add up to more than 5 and therefore be invalid.

It takes exponentially more dice throws to win, the lower the target gets. Eventually,

when the target is 2 (the minimum possible), only one throw out of every 36, or 2% of

them, will produce a winning result.

In Example 8-10, the winning “nonce” is 13 and this result can be confirmed by anyone

independently. Anyone can add the number 13 as a suffix to the phrase “I am Satoshi

Nakamoto” and compute the hash, verifying that it is less than the target. The successful

result is also proof of work, because it proves we did the work to find that nonce. While

it only takes one hash computation to verify, it took us 13 hash computations to find a

nonce that worked. If we had a lower target (higher difficulty) it would take many more

hash computations to find a suitable nonce, but only one hash computation for anyone

to verify. Furthermore, by knowing the target, anyone can estimate the difficulty using

statistics and therefore know how much work was needed to find such a nonce.

Bitcoin’s proof of work is very similar to the challenge shown in Example 8-10. The

miner constructs a candidate block filled with transactions. Next, the miner calculates

the hash of this block’s header and sees if it is smaller than the current *target*. If the hash

is not less than the target, the miner will modify the nonce (usually just incrementing

it by one) and try again. At the current difficulty in the bitcoin network, miners have to

try quadrillions of times before finding a nonce that results in a low enough block header

hash.

A very simplified proof-of-work algorithm is implemented in Python in Example 8-11.

*Example 8-11. Simplified proof-of-work implementation*

*#!/usr/bin/env python*

*# example of proof-of-work algorithm*

**import hashlib**

**import time**

max\_nonce = 2 \*\* 32 *# 4 billion*

**def** proof\_of\_work(header, difficulty\_bits):

*# calculate the difficulty target*

target = 2 \*\* (256-difficulty\_bits)

**for** nonce **in** xrange(max\_nonce):

hash\_result = hashlib.sha256(str(header)+str(nonce)).hexdigest()

*# check if this is a valid result, below the target*

Mining the Block | 191

**if** long(hash\_result, 16) < target:

**print** "Success with nonce %d" % nonce

**print** "Hash is %s" % hash\_result

**return** (hash\_result,nonce)

**print** "Failed after %d (max\_nonce) tries" % nonce

**return** nonce

**if** \_\_name\_\_ == '\_\_main\_\_':

nonce = 0

hash\_result = ''

*# difficulty from 0 to 31 bits*

**for** difficulty\_bits **in** xrange(32):

difficulty = 2 \*\* difficulty\_bits

**print** "Difficulty: %ld (%d bits)" % (difficulty, difficulty\_bits)

**print** "Starting search..."

*# checkpoint the current time*

start\_time = time.time()

*# make a new block which includes the hash from the previous block*

*# we fake a block of transactions - just a string*

new\_block = 'test block with transactions' + hash\_result

*# find a valid nonce for the new block*

(hash\_result, nonce) = proof\_of\_work(new\_block, difficulty\_bits)

*# checkpoint how long it took to find a result*

end\_time = time.time()

elapsed\_time = end\_time - start\_time

**print** "Elapsed Time: %.4f seconds" % elapsed\_time

**if** elapsed\_time > 0:

*# estimate the hashes per second*

hash\_power = float(long(nonce)/elapsed\_time)

**print** "Hashing Power: %ld hashes per second" % hash\_power

Running this code, you can set the desired difficulty (in bits, how many of the leading

bits must be zero) and see how long it takes for your computer to find a solution. In

Example 8-12, you can see how it works on an average laptop.

192 | Chapter 8: Mining and Consensus

*Example 8-12. Running the proof of work example for various difficulties*

$ python proof-of-work-example.py\*

Difficulty: 1 (0 bits)

[...]

Difficulty: 8 (3 bits)

Starting search...

Success with nonce 9

Hash is 1c1c105e65b47142f028a8f93ddf3dabb9260491bc64474738133ce5256cb3c1

Elapsed Time: 0.0004 seconds

Hashing Power: 25065 hashes per second

Difficulty: 16 (4 bits)

Starting search...

Success with nonce 25

Hash is 0f7becfd3bcd1a82e06663c97176add89e7cae0268de46f94e7e11bc3863e148

Elapsed Time: 0.0005 seconds

Hashing Power: 52507 hashes per second

Difficulty: 32 (5 bits)

Starting search...

Success with nonce 36

Hash is 029ae6e5004302a120630adcbb808452346ab1cf0b94c5189ba8bac1d47e7903

Elapsed Time: 0.0006 seconds

Hashing Power: 58164 hashes per second

[...]

Difficulty: 4194304 (22 bits)

Starting search...

Success with nonce 1759164

Hash is 0000008bb8f0e731f0496b8e530da984e85fb3cd2bd81882fe8ba3610b6cefc3

Elapsed Time: 13.3201 seconds

Hashing Power: 132068 hashes per second

Difficulty: 8388608 (23 bits)

Starting search...

Success with nonce 14214729

Hash is 000001408cf12dbd20fcba6372a223e098d58786c6ff93488a9f74f5df4df0a3

Elapsed Time: 110.1507 seconds

Hashing Power: 129048 hashes per second

Difficulty: 16777216 (24 bits)

Starting search...

Success with nonce 24586379

Hash is 0000002c3d6b370fccd699708d1b7cb4a94388595171366b944d68b2acce8b95

Elapsed Time: 195.2991 seconds

Hashing Power: 125890 hashes per second

[...]

Difficulty: 67108864 (26 bits)

Starting search...

Success with nonce 84561291

Mining the Block | 193

Hash is 0000001f0ea21e676b6dde5ad429b9d131a9f2b000802ab2f169cbca22b1e21a

Elapsed Time: 665.0949 seconds

Hashing Power: 127141 hashes per second

As you can see, increasing the difficulty by 1 bit causes an exponential increase in the

time it takes to find a solution. If you think of the entire 256-bit number space, each

time you constrain one more bit to zero, you decrease the search space by half. In

Example 8-12, it takes 84 million hash attempts to find a nonce that produces a hash

with 26 leading bits as zero. Even at a speed of more than 120,000 hashes per second, it

still requires 10 minutes on a consumer laptop to find this solution.

At the time of writing, the network is attempting to find a block whose header hash is

less than 000000000000004c296e6376db3a241271f43fd3f5de7ba18986e517a243baa7.

As you can see, there are a lot of zeros at the beginning of that hash, meaning that the

acceptable range of hashes is much smaller, hence it’s more difficult to find a valid hash.

It will take on average more than 150 quadrillion hash calculations per second for the

network to discover the next block. That seems like an impossible task, but fortunately

the network is bringing 100 petahashes per second (PH/sec) of processing power to

bear, which will be able to find a block in about 10 minutes on average.

Difficulty Representation

In Example 8-3, we saw that the block contains the difficulty target, in a notation called

“difficulty bits” or just “bits,” which in block 277,316 has the value of 0x1903a30c. This

notation expresses the difficulty target as a coefficient/exponent format, with the first

two hexadecimal digits for the exponent and the next six hex digits as the coefficient.

In this block, therefore, the exponent is 0x19 and the coefficient is 0x03a30c.

The formula to calculate the difficulty target from this representation is:

target = coefficient \* 2^(8 \* (exponent – 3))

Using that formula, and the difficulty bits value 0x1903a30c, we get:

target = 0x03a30c \* 2^(0x08 \* (0x19 - 0x03))^

=> target = 0x03a30c \* 2^(0x08 \* 0x16)^

=> target = 0x03a30c \* 2^0xB0^

which in decimal is:

=> target = 238,348 \* 2^176^

=> target =

22,829,202,948,393,929,850,749,706,076,701,368,331,072,452,018,388,575,715,328

switching back to hexadecimal:

=> target = 0x0000000000000003A30C00000000000000000000000000000000000000000000

194 | Chapter 8: Mining and Consensus

This means that a valid block for height 277,316 is one that has a block header hash that

is less than the target. In binary that number would have more than the first 60 bits set

to zero. With this level of difficulty, a single miner processing 1 trillion hashes per second

(1 tera-hash per second or 1 TH/sec) would only find a solution once every 8,496 blocks

or once every 59 days, on average.

Difficulty Target and Retargeting

As we saw, the target determines the difficulty and therefore affects how long it takes to

find a solution to the proof-of-work algorithm. This leads to the obvious questions:

Why is the difficulty adjustable, who adjusts it, and how?

Bitcoin’s blocks are generated every 10 minutes, on average. This is bitcoin’s heartbeat

and underpins the frequency of currency issuance and the speed of transaction settlement.

It has to remain constant not just over the short term, but over a period of many

decades. Over this time, it is expected that computer power will continue to increase at

a rapid pace. Furthermore, the number of participants in mining and the computers

they use will also constantly change. To keep the block generation time at 10 minutes,

the difficulty of mining must be adjusted to account for these changes. In fact, difficulty

is a dynamic parameter that will be periodically adjusted to meet a 10-minute block

target. In simple terms, the difficulty target is set to whatever mining power will result

in a 10-minute block interval.

How, then, is such an adjustment made in a completely decentralized network? Difficulty

retargeting occurs automatically and on every full node independently. Every 2,016

blocks, all nodes retarget the proof-of-work difficulty. The equation for retargeting difficulty

measures the time it took to find the last 2,016 blocks and compares that to the

expected time of 20,160 minutes (two weeks based upon a desired 10-minute block

time). The ratio between the actual timespan and desired timespan is calculated and a

corresponding adjustment (up or down) is made to the difficulty. In simple terms: If

the network is finding blocks faster than every 10 minutes, the difficulty increases. If

block discovery is slower than expected, the difficulty decreases.

The equation can be summarized as:

New Difficulty = Old Difficulty \* (Actual Time of Last 2016 Blocks / 20160 minutes)

Example 8-13 shows the code used in the Bitcoin Core client.

*Example 8-13. Retargeting the proof-of-work difficulty—GetNextWorkRequired() in*

*pow.cpp, line 43*

*// Go back by what we want to be 14 days worth of blocks*

**const** CBlockIndex\* pindexFirst = pindexLast;

**for** (**int** i = 0; pindexFirst && i < Params().Interval()-1; i++)

pindexFirst = pindexFirst->pprev;

assert(pindexFirst);

Mining the Block | 195

*// Limit adjustment step*

**int64\_t** nActualTimespan = pindexLast->GetBlockTime() - pindexFirst->GetBlockTime();

LogPrintf(" nActualTimespan = %d before bounds**\n**", nActualTimespan);

**if** (nActualTimespan < Params().TargetTimespan()/4)

nActualTimespan = Params().TargetTimespan()/4;

**if** (nActualTimespan > Params().TargetTimespan()\*4)

nActualTimespan = Params().TargetTimespan()\*4;

*// Retarget*

uint256 bnNew;

uint256 bnOld;

bnNew.SetCompact(pindexLast->nBits);

bnOld = bnNew;

bnNew \*= nActualTimespan;

bnNew /= Params().TargetTimespan();

**if** (bnNew > Params().ProofOfWorkLimit())

bnNew = Params().ProofOfWorkLimit();

The parameters Interval (2,016 blocks) and TargetTimespan (two weeks as 1,209,600

seconds) are defined in *chainparams.cpp*.

To avoid extreme volatility in the difficulty, the retargeting adjustment must be less than

a factor of four (4) per cycle. If the required difficulty adjustment is greater than a factor

of four, it will be adjusted by the maximum and not more. Any further adjustment will

be accomplished in the next retargeting period because the imbalance will persist

through the next 2,016 blocks. Therefore, large discrepancies between hashing power

and difficulty might take several 2,016 block cycles to balance out.

The difficulty of finding a bitcoin block is approximately *10 minutes*

*of processing* for the entire network, based on the time it took to find

the previous 2,016 blocks, adjusted every 2,016 blocks.

Note that the target difficulty is independent of the number of transactions or the value

of transactions. This means that the amount of hashing power and therefore electricity

expended to secure bitcoin is also entirely independent of the number of transactions.

Bitcoin can scale up, achieve broader adoption, and remain secure without any increase

in hashing power from today’s level. The increase in hashing power represents market

forces as new miners enter the market to compete for the reward. As long as enough

hashing power is under the control of miners acting honestly in pursuit of the reward,

it is enough to prevent “takeover” attacks and, therefore, it is enough to secure bitcoin.

The target difficulty is closely related to the cost of electricity and the exchange rate of

bitcoin vis-a-vis the currency used to pay for electricity. High-performance mining

196 | Chapter 8: Mining and Consensus

systems are about as efficient as possible with the current generation of silicon fabrication,

converting electricity into hashing computation at the highest rate possible. The

primary influence on the mining market is the price of one kilowatt-hour in bitcoin,

because that determines the profitability of mining and therefore the incentives to enter

or exit the mining market.

Successfully Mining the Block

As we saw earlier, Jing’s node has constructed a candidate block and prepared it for

mining. Jing has several hardware mining rigs with application-specific integrated circuits,

where hundreds of thousands of integrated circuits run the SHA256 algorithm in

parallel at incredible speeds. These specialized machines are connected to his mining

node over USB. Next, the mining node running on Jing’s desktop transmits the block

header to his mining hardware, which starts testing trillions of nonces per second.

Almost 11 minutes after starting to mine block 277,316, one of the hardware mining

machines finds a solution and sends it back to the mining node. When inserted into the

block header, the nonce 4,215,469,401 produces a block hash of:

0000000000000002a7bbd25a417c0374cc55261021e8a9ca74442b01284f0569

which is less than the target:

0000000000000003A30C00000000000000000000000000000000000000000000

Immediately, Jing’s mining node transmits the block to all its peers. They receive, validate,

and then propagate the new block. As the block ripples out across the network,

each node adds it to its own copy of the blockchain, extending it to a new height of

277,316 blocks. As mining nodes receive and validate the block, they abandon their

efforts to find a block at the same height and immediately start computing the next block

in the chain.

In the next section, we’ll look at the process each node uses to validate a block and select

the longest chain, creating the consensus that forms the decentralized blockchain.

Validating a New Block

The third step in bitcoin’s consensus mechanism is independent validation of each new

block by every node on the network. As the newly solved block moves across the network,

each node performs a series of tests to validate it before propagating it to its peers.

This ensures that only valid blocks are propagated on the network. The independent

validation also ensures that miners who act honestly get their blocks incorporated in

the blockchain, thus earning the reward. Those miners who act dishonestly have their

blocks rejected and not only lose the reward, but also waste the effort expended to find

a proof-of-work solution, thus incurring the cost of electricity without compensation.

Successfully Mining the Block | 197

When a node receives a new block, it will validate the block by checking it against a long

list of criteria that must all be met; otherwise, the block is rejected. These criteria can

be seen in the Bitcoin Core client in the functions CheckBlock and CheckBlockHead

er and include:

• The block data structure is syntactically valid

• The block header hash is less than the target difficulty (enforces the proof of work)

• The block timestamp is less than two hours in the future (allowing for time errors)

• The block size is within acceptable limits

• The first transaction (and only the first) is a coinbase generation transaction

• All transactions within the block are valid using the transaction checklist discussed

in “Independent Verification of Transactions” on page 177

The independent validation of each new block by every node on the network ensures

that the miners can’t cheat. In previous sections we saw how the miners get to write a

transaction that awards them the new bitcoins created within the block and claim the

transaction fees. Why don’t miners write themselves a transaction for a thousand bitcoin

instead of the correct reward? Because every node validates blocks according to the

same rules. An invalid coinbase transaction would make the entire block invalid, which

would result in the block being rejected and, therefore, that transaction would never

become part of the ledger. The miners have to construct a perfect block, based on the

shared rules that all nodes follow, and mine it with a correct solution to the proof of

work. To do so, they expend a lot of electricity in mining, and if they cheat, all the

electricity and effort is wasted. This is why independent validation is a key component

of decentralized consensus.

Assembling and Selecting Chains of Blocks

The final step in bitcoin’s decentralized consensus mechanism is the assembly of blocks

into chains and the selection of the chain with the most proof of work. Once a node has

validated a new block, it will then attempt to assemble a chain by connecting the block

to the existing blockchain.

Nodes maintain three sets of blocks: those connected to the main blockchain, those that

form branches off the main blockchain (secondary chains), and finally, blocks that do

not have a known parent in the known chains (orphans). Invalid blocks are rejected as

soon as any one of the validation criteria fails and are therefore not included in any

chain.

The “main chain” at any time is whichever chain of blocks has the most cumulative

difficulty associated with it. Under most circumstances this is also the chain with the

most blocks in it, unless there are two equal-length chains and one has more proof of

198 | Chapter 8: Mining and Consensus

work. The main chain will also have branches with blocks that are “siblings” to the blocks

on the main chain. These blocks are valid but not part of the main chain. They are kept

for future reference, in case one of those chains is extended to exceed the main chain

in difficulty. In the next section (“Blockchain Forks” on page 199), we will see how secondary

chains occur as a result of an almost simultaneous mining of blocks at the same

height.

When a new block is received, a node will try to slot it into the existing blockchain. The

node will look at the block’s “previous block hash” field, which is the reference to the

new block’s parent. Then, the node will attempt to find that parent in the existing blockchain.

Most of the time, the parent will be the “tip” of the main chain, meaning this new

block extends the main chain. For example, the new block 277,316 has a reference to

the hash of its parent block 277,315. Most nodes that receive 277,316 will already have

block 277,315 as the tip of their main chain and will therefore link the new block and

extend that chain.

Sometimes, as we will see in “Blockchain Forks” on page 199, the new block extends a

chain that is not the main chain. In that case, the node will attach the new block to the

secondary chain it extends and then compare the difficulty of the secondary chain to

the main chain. If the secondary chain has more cumulative difficulty than the main

chain, the node will *reconverge* on the secondary chain, meaning it will select the secondary

chain as its new main chain, making the old main chain a secondary chain. If

the node is a miner, it will now construct a block extending this new, longer, chain.

If a valid block is received and no parent is found in the existing chains, that block is

considered an “orphan.” Orphan blocks are saved in the orphan block pool where they

will stay until their parent is received. Once the parent is received and linked into the

existing chains, the orphan can be pulled out of the orphan pool and linked to the parent,

making it part of a chain. Orphan blocks usually occur when two blocks that were mined

within a short time of each other are received in reverse order (child before parent).

By selecting the greatest-difficulty chain, all nodes eventually achieve network-wide

consensus. Temporary discrepancies between chains are resolved eventually as more

proof of work is added, extending one of the possible chains. Mining nodes “vote” with

their mining power by choosing which chain to extend by mining the next block. When

they mine a new block and extend the chain, the new block itself represents their vote.

In the next section we will look at how discrepancies between competing chains (forks)

are resolved by the independent selection of the longest difficulty chain.

Blockchain Forks

Because the blockchain is a decentralized data structure, different copies of it are not

always consistent. Blocks might arrive at different nodes at different times, causing the

nodes to have different perspectives of the blockchain. To resolve this, each node always

Assembling and Selecting Chains of Blocks | 199

selects and attempts to extend the chain of blocks that represents the most proof of work,

also known as the longest chain or greatest cumulative difficulty chain. By summing

the difficulty recorded in each block in a chain, a node can calculate the total amount

of proof of work that has been expended to create that chain. As long as all nodes select

the longest cumulative difficulty chain, the global bitcoin network eventually converges

to a consistent state. Forks occur as temporary inconsistencies between versions of the

blockchain, which are resolved by eventual reconvergence as more blocks are added to

one of the forks.

In the next few diagrams, we follow the progress of a “fork” event across the network.

The diagram is a simplified representation of bitcoin as a global network. In reality, the

bitcoin network’s topology is not organized geographically. Rather, it forms a mesh

network of interconnected nodes, which might be located very far from each other

geographically. The representation of a geographic topology is a simplification used for

the purposes of illustrating a fork. In the real bitcoin network, the “distance” between

nodes is measured in “hops” from node to node, not on their physical location. For

illustration purposes, different blocks are shown as different colors, spreading across

the network and coloring the connections they traverse.

In the first diagram (Figure 8-2), the network has a unified perspective of the blockchain,

with the blue block as the tip of the main chain.

*Figure 8-2. Visualization of a blockchain fork event—before the fork*

A “fork” occurs whenever there are two candidate blocks competing to form the longest

blockchain. This occurs under normal conditions whenever two miners solve the proofof-

work algorithm within a short period of time from each other. As both miners discover

a solution for their respective candidate blocks, they immediately broadcast their

200 | Chapter 8: Mining and Consensus

own “winning” block to their immediate neighbors who begin propagating the block

across the network. Each node that receives a valid block will incorporate it into its

blockchain, extending the blockchain by one block. If that node later sees another candidate

block extending the same parent, it connects the second candidate on a secondary

chain. As a result, some nodes will “see” one candidate block first, while other nodes

will see the other candidate block and two competing versions of the blockchain will

emerge.

In Figure 8-3, we see two miners who mine two different blocks almost simultaneously.

Both of these blocks are children of the blue block, meant to extend the chain by building

on top of the blue block. To help us track it, one is visualized as a red block originating

from Canada, and the other is marked as a green block originating from Australia.

*Figure 8-3. Visualization of a blockchain fork event: two blocks found simultaneously*

Let’s assume, for example, that a miner in Canada finds a proof-of-work solution for a

block “red” that extends the blockchain, building on top of the parent block “blue.”

Almost simultaneously, an Australian miner who was also extending block “blue” finds

a solution for block “green,” his candidate block. Now, there are two possible blocks,

one we call “red,” originating in Canada, and one we call “green,” originating in Australia.

Both blocks are valid, both blocks contain a valid solution to the proof of work, and

both blocks extend the same parent. Both blocks likely contain most of the same transactions,

with only perhaps a few differences in the order of transactions.

As the two blocks propagate, some nodes receive block “red” first and some receive

block “green” first. As shown in Figure 8-4, the network splits into two different perspectives

of the blockchain, one side topped with a red block, the other with a green

block.

Assembling and Selecting Chains of Blocks | 201

*Figure 8-4. Visualization of a blockchain fork event: two blocks propagate, splitting the*

*network*

From that moment, the bitcoin network nodes closest (topologically, not geographically)

to the Canadian node will hear about block “red” first and will create a new

greatest-cumulative-difficulty blockchain with “red” as the last block in the chain (e.g.,

blue-red), ignoring the candidate block “green” that arrives a bit later. Meanwhile, nodes

closer to the Australian node will take that block as the winner and extend the blockchain

with “green” as the last block (e.g., blue-green), ignoring “red” when it arrives a few

seconds later. Any miners that saw “red” first will immediately build candidate blocks

that reference “red” as the parent and start trying to solve the proof of work for these

candidate blocks. The miners that accepted “green” instead will start building on top of

“green” and extending that chain.

Forks are almost always resolved within one block. As part of the network’s hashing

power is dedicated to building on top of “red” as the parent, another part of the hashing

power is focused on building on top of “green.” Even if the hashing power is almost

evenly split, it is likely that one set of miners will find a solution and propagate it before

the other set of miners have found any solutions. Let’s say, for example, that the miners

building on top of “green” find a new block “pink” that extends the chain (e.g., bluegreen-

pink). They immediately propagate this new block and the entire network sees it

as a valid solution as shown in Figure 8-5.

202 | Chapter 8: Mining and Consensus

*Figure 8-5. Visualization of a blockchain fork event: a new block extends one fork*

All nodes that had chosen “green” as the winner in the previous round will simply extend

the chain one more block. The nodes that chose “red” as the winner, however, will now

see two chains: blue-green-pink and blue-red. The chain blue-green-pink is now longer

(more cumulative difficulty) than the chain blue-red. As a result, those nodes will set

the chain blue-green-pink as main chain and change the blue-red chain to being a

secondary chain, as shown in Figure 8-6. This is a chain reconvergence, because those

nodes are forced to revise their view of the blockchain to incorporate the new evidence

of a longer chain. Any miners working on extending the chain blue-red will now stop

that work because their candidate block is an “orphan,” as its parent “red” is no longer

on the longest chain. The transactions within “red” are queued up again for processing

in the next block, because that block is no longer in the main chain. The entire network

re-converges on a single blockchain blue-green-pink, with “pink” as the last block in

the chain. All miners immediately start working on candidate blocks that reference

“pink” as their parent to extend the blue-green-pink chain.

Assembling and Selecting Chains of Blocks | 203

*Figure 8-6. Visualization of a blockchain fork event: the network reconverges on a new*

*longest chain*

It is theoretically possible for a fork to extend to two blocks, if two blocks are found

almost simultaneously by miners on opposite “sides” of a previous fork. However, the

chance of that happening is very low. Whereas a one-block fork might occur every week,

a two-block fork is exceedingly rare.

Bitcoin’s block interval of 10 minutes is a design compromise between fast confirmation

times (settlement of transactions) and the probability of a fork. A faster block time would

make transactions clear faster but lead to more frequent blockchain forks, whereas a

slower block time would decrease the number of forks but make settlement slower.

Mining and the Hashing Race

Bitcoin mining is an extremely competitive industry. The hashing power has increased

exponentially every year of bitcoin’s existence. Some years the growth has reflected a

complete change of technology, such as in 2010 and 2011 when many miners switched

from using CPU mining to GPU mining and field programmable gate array (FPGA)

mining. In 2013 the introduction of ASIC mining lead to another giant leap in mining

power, by placing the SHA256 function directly on silicon chips specialized for the

purpose of mining. The first such chips could deliver more mining power in a single

box than the entire bitcoin network in 2010.

The following list shows the total hashing power of the bitcoin network, over the first

five years of operation:

*2009*

0.5 MH/sec–8 MH/sec (16× growth)

204 | Chapter 8: Mining and Consensus

*2010*

8 MH/sec–116 GH/sec (14,500× growth)

*2011*

16 GH/sec–9 TH/sec (562× growth)

*2012*

9 TH/sec–23 TH/sec (2.5× growth)

*2013*

23 TH/sec–10 PH/sec (450× growth)

*2014*

10 PH/sec–150 PH/sec in August (15× growth)

In the chart in Figure 8-7, we see the bitcoin network’s hashing power increase over the

past two years. As you can see, the competition between miners and the growth of

bitcoin has resulted in an exponential increase in the hashing power (total hashes per

second across the network).

*Figure 8-7. Total hashing power, gigahashes per second, over two years*

As the amount of hashing power applied to mining bitcoin has exploded, the difficulty

has risen to match it. The difficulty metric in the chart shown in Figure 8-8 is measured

as a ratio of current difficulty over minimum difficulty (the difficulty of the first block).

Mining and the Hashing Race | 205

*Figure 8-8. Bitcoin’s mining difficulty metric, over two years*

In the last two years, the ASIC mining chips have become increasingly denser, approaching

the cutting edge of silicon fabrication with a feature size (resolution) of 22

nanometers (nm). Currently, ASIC manufacturers are aiming to overtake generalpurpose

CPU chip manufacturers, designing chips with a feature size of 16nm, because

the profitability of mining is driving this industry even faster than general computing.

There are no more giant leaps left in bitcoin mining, because the industry has reached

the forefront of Moore’s Law, which stipulates that computing density will double approximately

every 18 months. Still, the mining power of the network continues to advance

at an exponential pace as the race for higher density chips is matched with a race

for higher density data centers where thousands of these chips can be deployed. It’s no

longer about how much mining can be done with one chip, but how many chips can be

squeezed into a building, while still dissipating the heat and providing adequate power.

The Extra Nonce Solution

Since 2012, bitcoin mining has evolved to resolve a fundamental limitation in the structure

of the block header. In the early days of bitcoin, a miner could find a block by

iterating through the nonce until the resulting hash was below the target. As difficulty

increased, miners often cycled through all 4 billion values of the nonce without finding

a block. However, this was easily resolved by updating the block timestamp to account

for the elapsed time. Because the timestamp is part of the header, the change would

allow miners to iterate through the values of the nonce again with different results. Once

mining hardware exceeded 4 GH/sec, however, this approach became increasingly difficult

because the nonce values were exhausted in less than a second. As ASIC mining

equipment started pushing and then exceeding the TH/sec hash rate, the mining software

needed more space for nonce values in order to find valid blocks. The timestamp

could be stretched a bit, but moving it too far into the future would cause the block to

become invalid. A new source of “change” was needed in the block header. The solution

206 | Chapter 8: Mining and Consensus

was to use the coinbase transaction as a source of extra nonce values. Because the coinbase

script can store between 2 and 100 bytes of data, miners started using that space

as extra nonce space, allowing them to explore a much larger range of block header

values to find valid blocks. The coinbase transaction is included in the merkle tree,

which means that any change in the coinbase script causes the merkle root to change.

Eight bytes of extra nonce, plus the 4 bytes of “standard” nonce allow miners to explore

a total 296 (8 followed by 28 zeros) possibilities *per second* without having to modify the

timestamp. If, in the future, miners could run through all these possibilities, they could

then modify the timestamp. There is also more space in the coinbase script for future

expansion of the extra nonce space.

Mining Pools

In this highly competitive environment, individual miners working alone (also known

as solo miners) don’t stand a chance. The likelihood of them finding a block to offset

their electricity and hardware costs is so low that it represents a gamble, like playing the

lottery. Even the fastest consumer ASIC mining system cannot keep up with commercial

systems that stack tens of thousands of these chips in giant warehouses near hydroelectric

power stations. Miners now collaborate to form mining pools, pooling their

hashing power and sharing the reward among thousands of participants. By participating

in a pool, miners get a smaller share of the overall reward, but typically get

rewarded every day, reducing uncertainty.

Let’s look at a specific example. Assume a miner has purchased mining hardware with

a combined hashing rate of 6,000 gigahashes per second (GH/s), or 6 TH/s. In August

of 2014 this equipment costs approximately $10,000. The hardware consumes 3 kilowatts

(kW) of electricity when running, 72 kW-hours a day, at a cost of $7 or $8 per day

on average. At current bitcoin difficulty, the miner will be able to solo mine a block

approximately once every 155 days, or every 5 months. If the miner does find a single

block in that timeframe, the payout of 25 bitcoins, at approximately $600 per bitcoin,

will result in a single payout of $15,000, which will cover the entire cost of the hardware

and the electricity consumed over the time period, leaving a net profit of approximately

$3,000. However, the chance of finding a block in a five-month period depends on the

miner’s luck. He might find two blocks in five months and make a very large profit. Or

he might not find a block for 10 months and suffer a financial loss. Even worse, the

difficulty of the bitcoin proof-of-work algorithm is likely to go up significantly over that

period, at the current rate of growth of hashing power, meaning the miner has, at most,

six months to break even before the hardware is effectively obsolete and must be replaced

by more powerful mining hardware. If this miner participates in a mining pool, instead

of waiting for a once-in-five-months $15,000 windfall, he will be able to earn approximately

$500 to $750 per week. The regular payouts from a mining pool will help him

amortize the cost of hardware and electricity over time without taking an enormous

Mining and the Hashing Race | 207

risk. The hardware will still be obsolete in six to nine months and the risk is still high,

but the revenue is at least regular and reliable over that period.

Mining pools coordinate many hundreds or thousands of miners, over specialized poolmining

protocols. The individual miners configure their mining equipment to connect

to a pool server, after creating an account with the pool. Their mining hardware remains

connected to the pool server while mining, synchronizing their efforts with the other

miners. Thus, the pool miners share the effort to mine a block and then share in the

rewards.

Successful blocks pay the reward to a pool bitcoin address, rather than individual miners.

The pool server will periodically make payments to the miners’ bitcoin addresses,

once their share of the rewards has reached a certain threshold. Typically, the pool server

charges a percentage fee of the rewards for providing the pool-mining service.

Miners participating in a pool split the work of searching for a solution to a candidate

block, earning “shares” for their mining contribution. The mining pool sets a lower

difficulty target for earning a share, typically more than 1,000 times easier than the

bitcoin network’s difficulty. When someone in the pool successfully mines a block, the

reward is earned by the pool and then shared with all miners in proportion to the

number of shares they contributed to the effort.

Pools are open to any miner, big or small, professional or amateur. A pool will therefore

have some participants with a single small mining machine, and others with a garage

full of high-end mining hardware. Some will be mining with a few tens of a kilowatt of

electricity, others will be running a data center consuming a megawatt of power. How

does a mining pool measure the individual contributions, so as to fairly distribute the

rewards, without the possibility of cheating? The answer is to use bitcoin’s proof-ofwork

algorithm to measure each pool miner’s contribution, but set at a lower difficulty

so that even the smallest pool miners win a share frequently enough to make it worthwhile

to contribute to the pool. By setting a lower difficulty for earning shares, the pool

measures the amount of work done by each miner. Each time a pool miner finds a block

header hash that is less than the pool difficulty, she proves she has done the hashing

work to find that result. More importantly, the work to find shares contributes, in a

statistically measurable way, to the overall effort to find a hash lower than the bitcoin

network’s target. Thousands of miners trying to find low-value hashes will eventually

find one low enough to satisfy the bitcoin network target.

Let’s return to the analogy of a dice game. If the dice players are throwing dice with a

goal of throwing less than four (the overall network difficulty), a pool would set an easier

target, counting how many times the pool players managed to throw less than eight.

When pool players throw less than eight (the pool share target), they earn shares, but

they don’t win the game because they don’t achieve the game target (less than four). The

pool players will achieve the easier pool target much more often, earning them shares

very regularly, even when they don’t achieve the harder target of winning the game.

208 | Chapter 8: Mining and Consensus

Every now and then, one of the pool players will throw a combined dice throw of less

than four and the pool wins. Then, the earnings can be distributed to the pool players

based on the shares they earned. Even though the target of eight-or-less wasn’t winning,

it was a fair way to measure dice throws for the players, and it occasionally produces a

less-than-four throw.

Similarly, a mining pool will set a pool difficulty that will ensure that an individual pool

miner can find block header hashes that are less than the pool difficulty quite often,

earning shares. Every now and then, one of these attempts will produce a block header

hash that is less than the bitcoin network target, making it a valid block and the whole

pool wins.

Managed pools

Most mining pools are “managed,” meaning that there is a company or individual running

a pool server. The owner of the pool server is called the *pool operator*, and he

charges pool miners a percentage fee of the earnings.

The pool server runs specialized software and a pool-mining protocol that coordinates

the activities of the pool miners. The pool server is also connected to one or more full

bitcoin nodes and has direct access to a full copy of the blockchain database. This allows

the pool server to validate blocks and transactions on behalf of the pool miners, relieving

them of the burden of running a full node. For pool miners, this is an important consideration,

because a full node requires a dedicated computer with at least 15 to 20 GB

of persistent storage (disk) and at least 2 GB of memory (RAM). Furthermore, the

bitcoin software running on the full node needs to be monitored, maintained, and upgraded

frequently. Any downtime caused by a lack of maintenance or lack of resources

will hurt the miner’s profitability. For many miners, the ability to mine without running

a full node is another big benefit of joining a managed pool.

Pool miners connect to the pool server using a mining protocol such as Stratum (STM)

or GetBlockTemplate (GBT). An older standard called GetWork (GWK) has been

mostly obsolete since late 2012, because it does not easily support mining at hash rates

above 4 GH/s. Both the STM and GBT protocols create block *templates* that contain a

template of a candidate block header. The pool server constructs a candidate block by

aggregating transactions, adding a coinbase transaction (with extra nonce space), calculating

the merkle root, and linking to the previous block hash. The header of the

candidate block is then sent to each of the pool miners as a template. Each pool miner

then mines using the block template, at a lower difficulty than the bitcoin network

difficulty, and sends any successful results back to the pool server to earn shares.

P2Pool

Managed pools create the possibility of cheating by the pool operator, who might direct

the pool effort to double-spend transactions or invalidate blocks (see “Consensus At‐

Mining and the Hashing Race | 209

tacks” on page 210). Furthermore, centralized pool servers represent a single-point-offailure.

If the pool server is down or is slowed by a denial-of-service attack, the pool

miners cannot mine. In 2011, to resolve these issues of centralization, a new pool mining

method was proposed and implemented: P2Pool is a peer-to-peer mining pool, without

a central operator.

P2Pool works by decentralizing the functions of the pool server, implementing a parallel

blockchain-like system called a *share chain*. A share chain is a blockchain running at a

lower difficulty than the bitcoin blockchain. The share chain allows pool miners to

collaborate in a decentralized pool, by mining shares on the share chain at a rate of one

share block every 30 seconds. Each of the blocks on the share chain records a proportionate

share reward for the pool miners who contribute work, carrying the shares

forward from the previous share block. When one of the share blocks also achieves the

difficulty target of the bitcoin network, it is propagated and included on the bitcoin

blockchain, rewarding all the pool miners who contributed to all the shares that preceded

the winning share block. Essentially, instead of a pool server keeping track of pool

miner shares and rewards, the share chain allows all pool miners to keep track of all

shares using a decentralized consensus mechanism like bitcoin’s blockchain consensus

mechanism.

P2Pool mining is more complex than pool mining because it requires that the pool

miners run a dedicated computer with enough disk space, memory, and Internet bandwidth

to support a full bitcoin node and the P2Pool node software. P2Pool miners

connect their mining hardware to their local P2Pool node, which simulates the functions

of a pool server by sending block templates to the mining hardware. On P2Pool, individual

pool miners construct their own candidate blocks, aggregating transactions much

like solo miners, but then mine collaboratively on the share chain. P2Pool is a hybrid

approach that has the advantage of much more granular payouts than solo mining, but

without giving too much control to a pool operator like managed pools.

Recently, participation in P2Pool has increased significantly as mining concentration

in mining pools has approached levels that create concerns of a 51% attack (see “Consensus

Attacks” on page 210). Further development of the P2Pool protocol continues with

the expectation of removing the need for running a full node and therefore making

decentralized mining even easier to use.

Consensus Attacks

Bitcoin’s consensus mechanism is, at least theoretically, vulnerable to attack by miners

(or pools) that attempt to use their hashing power to dishonest or destructive ends. As

we saw, the consensus mechanism depends on having a majority of the miners acting

honestly out of self-interest. However, if a miner or group of miners can achieve a

significant share of the mining power, they can attack the consensus mechanism so as

to disrupt the security and availability of the bitcoin network.

210 | Chapter 8: Mining and Consensus

It is important to note that consensus attacks can only affect future consensus, or at best

the most recent past (tens of blocks). Bitcoin’s ledger becomes more and more immutable

as time passes. While in theory, a fork can be achieved at any depth, in practice, the

computing power needed to force a very deep fork is immense, making old blocks

practically immutable. Consensus attacks also do not affect the security of the private

keys and signing algorithm (ECDSA). A consensus attack cannot steal bitcoins, spend

bitcoins without signatures, redirect bitcoins, or otherwise change past transactions or

ownership records. Consensus attacks can only affect the most recent blocks and cause

denial-of-service disruptions on the creation of future blocks.

One attack scenario against the consensus mechanism is called the “51% attack.” In this

scenario a group of miners, controlling a majority (51%) of the total network’s hashing

power, collude to attack bitcoin. With the ability to mine the majority of the blocks, the

attacking miners can cause deliberate “forks” in the blockchain and double-spend

transactions or execute denial-of-service attacks against specific transactions or addresses.

A fork/double-spend attack is one where the attacker causes previously confirmed

blocks to be invalidated by forking below them and re-converging on an alternate

chain. With sufficient power, an attacker can invalidate six or more blocks in a row,

causing transactions that were considered immutable (six confirmations) to be invalidated.

Note that a double-spend can only be done on the attacker’s own transactions,

for which the attacker can produce a valid signature. Double-spending one’s own transactions

is profitable if by invalidating a transaction the attacker can get a nonreversible

exchange payment or product without paying for it.

Let’s examine a practical example of a 51% attack. In the first chapter, we looked at a

transaction between Alice and Bob for a cup of coffee. Bob, the cafe owner, is willing to

accept payment for cups of coffee without waiting for confirmation (mining in a block),

because the risk of a double-spend on a cup of coffee is low in comparison to the convenience

of rapid customer service. This is similar to the practice of coffee shops that

accept credit card payments without a signature for amounts below $25, because the

risk of a credit-card chargeback is low while the cost of delaying the transaction to obtain

a signature is comparatively larger. In contrast, selling a more expensive item for bitcoin

runs the risk of a double-spend attack, where the buyer broadcasts a competing transaction

that spends the same inputs (UTXO) and cancels the payment to the merchant.

A double-spend attack can happen in two ways: either before a transaction is confirmed,

or if the attacker takes advantage of a blockchain fork to undo several blocks. A 51%

attack allows attackers to double-spend their own transactions in the new chain, thus

undoing the corresponding transaction in the old chain.

In our example, malicious attacker Mallory goes to Carol’s gallery and purchases a

beautiful triptych painting depicting Satoshi Nakamoto as Prometheus. Carol sells “The

Great Fire” paintings for $250,000 in bitcoin, to Mallory. Instead of waiting for six or

more confirmations on the transaction, Carol wraps and hands the paintings to Mallory

after only one confirmation. Mallory works with an accomplice, Paul, who operates a

Consensus Attacks | 211

large mining pool, and the accomplice launches a 51% attack as soon as Mallory’s transaction

is included in a block. Paul directs the mining pool to re-mine the same block

height as the block containing Mallory’s transaction, replacing Mallory’s payment to

Carol with a transaction that double-spends the same input as Mallory’s payment. The

double-spend transaction consumes the same UTXO and pays it back to Mallory’s wallet,

instead of paying it to Carol, essentially allowing Mallory to keep the bitcoin. Paul

then directs the mining pool to mine an additional block, so as to make the chain containing

the double-spend transaction longer than the original chain (causing a fork

below the block containing Mallory’s transaction). When the blockchain fork resolves

in favor of the new (longer) chain, the double-spent transaction replaces the original

payment to Carol. Carol is now missing the three paintings and also has no bitcoin

payment. Throughout all this activity, Paul’s mining pool participants might remain

blissfully unaware of the double-spend attempt, because they mine with automated

miners and cannot monitor every transaction or block.

To protect against this kind of attack, a merchant selling large-value items must wait at

least six confirmations before giving the product to the buyer. Alternatively, the merchant

should use an escrow multi-signature account, again waiting for several confirmations

after the escrow account is funded. The more confirmations elapse, the harder

it becomes to invalidate a transaction with a 51% attack. For high-value items, payment

by bitcoin will still be convenient and efficient even if the buyer has to wait 24 hours for

delivery, which would ensure 144 confirmations.

In addition to a double-spend attack, the other scenario for a consensus attack is to deny

service to specific bitcoin participants (specific bitcoin addresses). An attacker with a

majority of the mining power can simply ignore specific transactions. If they are included

in a block mined by another miner, the attacker can deliberately fork and remine

that block, again excluding the specific transactions. This type of attack can result

in a sustained denial of service against a specific address or set of addresses for as long

as the attacker controls the majority of the mining power.

Despite its name, the 51% attack scenario doesn’t actually require 51% of the hashing

power. In fact, such an attack can be attempted with a smaller percentage of the hashing

power. The 51% threshold is simply the level at which such an attack is almost guaranteed

to succeed. A consensus attack is essentially a tug-of-war for the next block and the

“stronger” group is more likely to win. With less hashing power, the probability of

success is reduced, because other miners control the generation of some blocks with

their “honest” mining power. One way to look at it is that the more hashing power an

attacker has, the longer the fork he can deliberately create, the more blocks in the recent

past he can invalidate, or the more blocks in the future he can control. Security research

groups have used statistical modeling to claim that various types of consensus attacks

are possible with as little as 30% of the hashing power.

212 | Chapter 8: Mining and Consensus

The massive increase of total hashing power has arguably made bitcoin impervious to

attacks by a single miner. There is no possible way for a solo miner to control even 1%

of the total mining power. However, the centralization of control caused by mining pools

has introduced the risk of for-profit attacks by a mining pool operator. The pool operator

in a managed pool controls the construction of candidate blocks and also controls which

transactions are included. This gives the pool operator the power to exclude transactions

or introduce double-spend transactions. If such abuse of power is done in a limited and

subtle way, a pool operator could conceivably profit from a consensus attack without

being noticed.

Not all attackers will be motivated by profit, however. One potential attack scenario is

where an attacker intends to disrupt the bitcoin network without the possibility of

profiting from such disruption. A malicious attack aimed at crippling bitcoin would

require enormous investment and covert planning, but could conceivably be launched

by a well-funded, most likely state-sponsored, attacker. Alternatively, a well-funded

attacker could attack bitcoin’s consensus by simultaneously amassing mining hardware,

compromising pool operators and attacking other pools with denial-of-service. All of

these scenarios are theoretically possible, but increasingly impractical as the bitcoin

network’s overall hashing power continues to grow exponentially. Recent advancements

in bitcoin, such as P2Pool mining, aim to further decentralize mining control, making

bitcoin consensus even harder to attack.

Undoubtedly, a serious consensus attack would erode confidence in bitcoin in the short

term, possibly causing a significant price decline. However, the bitcoin network and

software are constantly evolving, so consensus attacks would be met with immediate

countermeasures by the bitcoin community, making bitcoin hardier, stealthier, and

more robust than ever.

Consensus Attacks | 213

CHAPTER 9

Alternative Chains, Currencies,

and Applications

Bitcoin was the result of 20 years of research in distributed systems and currencies and

brought a revolutionary new technology into the space: the decentralized consensus

mechanism based on proof of work. This invention at the heart of bitcoin has ushered

a wave of innovation in currencies, financial services, economics, distributed systems,

voting systems, corporate governance, and contracts.

In this chapter we’ll examine the many offshoots of the bitcoin and blockchain inventions:

the alternative chains, currencies, and applications built since the introduction of

this technology in 2009. Mostly, we will look at alternative coins, or *alt coins*, which are

digital currencies implemented using the same design pattern as bitcoin, but with a

completely separate blockchain and network.

For every alt coin mentioned in this chapter, 50 or more will go unmentioned, eliciting

howls of anger from their creators and fans. The purpose of this chapter is not to evaluate

or qualify alt coins, or even to mention the most significant ones based on some subjective

assessment. Instead, we will highlight a few examples that show the breadth and

variety of the ecosystem, noting the first-of-a-kind for each innovation or significant

differentiation. Some of the most interesting examples of alt coins are in fact complete

failures from a monetary perspective. That perhaps makes them even more interesting

for study and highlights the fact that this chapter is not to be used as an investment

guide.

With new coins introduced every day, it would be impossible not to miss some important

coin, perhaps the one that changes history. The rate of innovation is what makes this

space so exciting and guarantees this chapter will be incomplete and out-of-date as soon

as it is published.

215

A Taxonomy of Alternative Currencies and Chains

Bitcoin is an open source project, and its code has been used as the basis for many other

software projects. The most common form of software spawned from bitcoin’s source

code are alternative decentralized currencies, or *alt coins*, which use the same basic

building blocks to implement digital currencies.

There are a number of protocol layers implemented on top of bitcoin’s blockchain.

These *meta coins*, *meta chains*, or *blockchain apps* use the blockchain as an application

platform or extend the bitcoin protocol by adding protocol layers. Examples include

Colored Coins, Mastercoin, and Counterparty.

In the next section we will examine a few notable alt coins, such as Litecoin, Dogecoin,

Freicoin, Primecoin, Peercoin, Darkcoin, and Zerocoin. These alt coins are notable for

historical reasons or because they are good examples for a specific type of alt coin innovation,

not because they are the most valuable or “best” alt coins.

In addition to the alt coins, there are also a number of alternative blockchain implementations

that are not really “coins,” which I call *alt chains*. These alt chains implement

a consensus algorithm and distributed ledger as a platform for contracts, name registration,

or other applications. Alt chains use the same basic building blocks and sometimes

also use a currency or token as a payment mechanism, but their primary purpose

is not currency. We will look at Namecoin, Ethereum, and NXT as examples of alt chains.

In addition to the proof-of-work consensus mechanism used in bitcoin, alternatives

include experimental protocols based on proof of resource and proof of publishing. We

will examine Maidsafe and Twister as examples of these consensus mechanisms.

Finally, there are a number of bitcoin contenders that offer digital currency or digital

payment networks, but without using a decentralized ledger or consensus mechanism

based on proof of work, such as Ripple and others. These non–blockchain technologies

are outside the scope of this book and will not be covered in this chapter.

Meta Coin Platforms

Meta coins and meta chains are software layers implemented on top of bitcoin, either

implementing a currency-inside-a-currency, or a platform/protocol overlay inside the

bitcoin system. These function layers extend the core bitcoin protocol and add features

and capabilities by encoding additional data inside bitcoin transactions and bitcoin

addresses. The first implementations of meta coins used various hacks to add metadata

to the bitcoin blockchain, such as using bitcoin addresses to encode data or using unused

transaction fields (e.g., the transaction sequence field) to encode metadata about the

added protocol layer. Since the introduction of the OP\_RETURN transaction scripting

opcode, the meta coins have been able to record metadata more directly in the blockchain,

and most are migrating to using that instead.

216 | Chapter 9: Alternative Chains, Currencies, and Applications

Colored Coins

*Colored coins* is a meta protocol that overlays information on small amounts of bitcoin.

A “colored” coin is an amount of bitcoin repurposed to express another asset. Imagine,

for example, taking a $1 note and putting a stamp on it that said, “This is a 1 share

certificate of Acme Inc.” Now the $1 serves two purposes: it is a currency note and also

a share certificate. Because it is more valuable as a share, you would not want to use it

to buy candy, so effectively it is no longer useful as currency. Colored coins work in the

same way by converting a specific, very small amount of bitcoin into a traded certificate

that represents another asset. The term “color” refers to the idea of giving special meaning

through the addition of an attribute such as a color—it is a metaphor, not an actual

color association. There are no colors in colored coins.

Colored coins are managed by specialized wallets that record and interpret the metadata

attached to the colored bitcoins. Using such a wallet, the user will convert an amount

of bitcoins from uncolored currency into colored coins by adding a label that has a

special meaning. For example, a label could represent stock certificates, coupons, real

property, commodities, or collectible tokens. It is entirely up to the users of colored

coins to assign and interpret the meaning of the “color” associated with specific coins.

To color the coins, the user defines the associated metadata, such as the type of issuance,

whether it can be subdivided into smaller units, a symbol and description, and other

related information. Once colored, these coins can be bought and sold, subdivided, and

aggregated, and receive dividend payments. The colored coins can also be “uncolored”

by removing the special association and redeemed for their face value in bitcoin.

To demonstrate the use of colored coins, we have created a set of 20 colored coins with

symbol “MasterBTC” that represent coupons for a free copy of this book shown in

Example 9-1. Each unit of MasterBTC, represented by these colored coins, can now be

sold or given to any bitcoin user with a colored-coin-capable wallet, who can then

transfer them to others or redeem them with the issuer for a free copy of the book. This

example of colored coins can be seen here.

*Example 9-1. The metadata profile of the colored coins recorded as a coupon for a free*

*copy of the book*

{

**"source\_addresses"**: [

"3NpZmvSPLmN2cVFw1pY7gxEAVPCVfnWfVD"

],

**"contract\_url"**: "https://www.coinprism.info/asset/

3NpZmvSPLmN2cVFw1pY7gxEAVPCVfnWfVD",

**"name\_short"**: "MasterBTC",

**"name"**: "Free copy of \"Mastering Bitcoin\"",

**"issuer"**: "Andreas M. Antonopoulos",

**"description"**: "This token is redeemable for a free copy of the book \"Mastering

Bitcoin\"",

**"description\_mime"**: "text/x-markdown; charset=UTF-8",

Meta Coin Platforms | 217

**"type"**: "Other",

**"divisibility"**: 0,

**"link\_to\_website"**: **false**,

**"icon\_url"**: **null**,

**"image\_url"**: **null**,

**"version"**: "1.0"

}

Mastercoin

Mastercoin is a protocol layer on top of bitcoin that supports a platform for various

applications extending the bitcoin system. Mastercoin uses the currency MST as a token

for conducting Mastercoin transactions but it is not primarily a currency. Rather, it is

a platform for building other things, such as user currencies, smart property tokens, decentralized

asset exchanges, and contracts. Think of Mastercoin as an application-layer

protocol on top of bitcoin’s financial transaction transport layer, just like HTTP runs

on top of TCP.

Mastercoin operates primarily through transactions sent to and from a special bitcoin

address called the “exodus” address (1EXoDusjGwvnjZUyKkxZ4UHEf77z6A5S4P), just like

HTTP uses a specific TCP port (port 80) to differentiate its traffic from the rest of the

TCP traffic. The Mastercoin protocol is gradually transitioning from using the specialized

exodus address and multi-signatures to using the OP\_RETURN bitcoin operator

to encode transaction metadata.

Counterparty

Counterparty is another protocol layer implemented on top of bitcoin. Counterparty

enables user currencies, tradable tokens, financial instruments, decentralized asset exchanges,

and other features. Counterparty is implemented primarily using the OP\_RE

TURN operator in bitcoin’s scripting language to record metadata that enhances bitcoin

transactions with additional meaning. Counterparty uses the currency XCP as a token

for conducting Counterparty transactions.

Alt Coins

The vast majority of alt coins are derived from bitcoin’s source code, also known as

“forks.” Some are implemented “from scratch” based on the blockchain model but

without using any of bitcoin’s source code. Alt coins and alt chains (in the next section)

are both separate implementations of blockchain technology and both forms use their

own blockchain. The difference in the terms is to indicate that alt coins are primarily

used as currency, whereas alt chains are used for other purposes, not primarily currency.

Strictly speaking, the first major “alt” fork of bitcoin’s code was not an alt coin but the

alt chain *Namecoin*, which we will discuss in the next section.

218 | Chapter 9: Alternative Chains, Currencies, and Applications

Based on the date of announcement, the first alt coin that was a fork of bitcoin appeared

in August 2011; it was called *IXCoin*. IXCoin modified a few of the bitcoin parameters,

specifically accelerating the creation of currency by increasing the reward to 96 coins

per block.

In September 2011, *Tenebrix* was launched. Tenebrix was the first cryptocurrency to

implement an alternative proof-of-work algorithm, namely *scrypt*, an algorithm originally

designed for password stretching (brute-force resistance). The stated goal of Tenebrix

was to make a coin that was resistant to mining with GPUs and ASICs, by using

a memory-intensive algorithm. Tenebrix did not succeed as a currency, but it was the

basis for Litecoin, which has enjoyed great success and has spawned hundreds of clones.

*Litecoin*, in addition to using scrypt as the proof-of-work algorithm, also implemented

a faster block-generation time, targeted at 2.5 minutes instead of bitcoin’s 10 minutes.

The resulting currency is touted as “silver to bitcoin’s gold” and is intended as a lightweight

alternative currency. Due to the faster confirmation time and the 84 million total

currency limit, many adherents of Litecoin believe it is better suited for retail transactions

than bitcoin.

Alt coins continued to proliferate in 2011 and 2012, either based on bitcoin or on Litecoin.

By 2013, there were 20 alt coins vying for position in the market. By the end of

2013, this number had exploded to 200, with 2013 quickly becoming the “year of the

alt coins.” The growth of alt coins continued in 2014, with more than 500 alt coins in

existence at the time of writing. More than half the alt coins today are clones of Litecoin.

Creating an alt coin is easy, which is why there are now more than 500 of them. Most

of the alt coins differ very slightly from bitcoin and do not offer anything worth studying.

Many are in fact just attempts to enrich their creators. Among the copycats and pumpand-

dump schemes, there are, however, some notable exceptions and very important

innovations. These alt coins take radically different approaches or add significant innovation

to bitcoin’s design pattern. There are three primary areas where these alt coins

differentiate from bitcoin:

• Different monetary policy

• Different proof of work or consensus mechanism

• Specific features, such as strong anonymity

For more information, see this graphical timeline of alt coins and alt chains.

Evaluating an Alt Coin

With so many alt coins out there, how does one decide which ones are worthy of attention?

Some alt coins attempt to achieve broad distribution and use as currencies.

Others are laboratories for experimenting on different features and monetary models.

Alt Coins | 219

Many are just get-rich-quick schemes by their creators. To evaluate alt coins, I look at

their defining characteristics and their market metrics.

Here are some questions to ask about how well an alt coin differentiates from bitcoin:

• Does the alt coin introduce a significant innovation?

• Is the difference compelling enough to attract users away from bitcoin?

• Does the alt coin address an interesting niche market or application?

• Can the alt coin attract enough miners to be secured against consensus attacks?

Here are some of the key financial and market metrics to consider:

• What is the total market capitalization of alt coin?

• How many estimated users/wallets does the alt coin have?

• How many merchants accept the alt coin?

• How many daily transactions (volume) are executed on the alt coin?

• How much value is transacted daily?

In this chapter, we will concentrate primarily on the technical characteristics and innovation

potential of alt coins represented by the first set of questions.

Monetary Parameter Alternatives: Litecoin, Dogecoin, Freicoin

Bitcoin has a few monetary parameters that give it distinctive characteristics of a deflationary

fixed-issuance currency. It is limited to 21 million major currency units (or

21 quadrillion minor units), it has a geometrically declining issuance rate, and it has a

10-minute block “heartbeat,” which controls the speed of transaction confirmation and

currency generation. Many alt coins have tweaked the primary parameters to achieve

different monetary policies. Among the hundreds of alt coins, some of the most notable

examples include the following.

Litecoin

One of the first alt coins, released in 2011, Litecoin is the second most successful digital

currency after bitcoin. Its primary innovations were the use of *scrypt* as the proof-ofwork

algorithm (inherited from Tenebrix) and its faster/lighter currency parameters.

• Block generation time: 2.5 minutes

• Total currency: 84 million coins by 2140

• Consensus algorithm: Scrypt proof of work

• Market capitalization: $160 million in mid-2014

220 | Chapter 9: Alternative Chains, Currencies, and Applications

Dogecoin

Dogecoin was released in December 2013, based on a fork of Litecoin. Dogecoin is

notable because it has a monetary policy of rapid issuance and a very high currency cap,

to encourage spending and tipping. Dogecoin is also notable because it was started as

a joke but became quite popular, with a large and active community, before declining

rapidly in 2014.

• Block generation time: 60 seconds

• Total currency: 100,000,000,000 (100 billion) Doge by 2015

• Consensus algorithm: Scrypt proof of work

• Market capitalization: $12 million in mid-2014

Freicoin

Freicoin was introduced in July 2012. It is a *demurrage currency*, meaning it has a negative

interest rate for stored value. Value stored in Freicoin is assessed a 4.5% APR fee,

to encourage consumption and discourage hoarding of money. Freicoin is notable in

that it implements a monetary policy that is the exact opposite of Bitcoin’s deflationary

policy. Freicoin has not seen success as a currency, but it is an interesting example of

the variety of monetary policies that can be expressed by alt coins.

• Block generation: 10 minutes

• Total currency: 100 million coins by 2140

• Consensus algorithm: SHA256 proof of work

• Market capitalization: $130,000 in mid-2014

Consensus Innovation: Peercoin, Myriad, Blackcoin, Vericoin, NXT

Bitcoin’s consensus mechanism is based on proof of work using the SHA256 algorithm.

The first alt coins introduced scrypt as an alternative proof-of-work algorithm, as a way

to make mining more CPU-friendly and less susceptible to centralization with ASICs.

Since then, innovation in the consensus mechanism has continued at a frenetic pace.

Several alt coins adopted a variety of algorithms such as scrypt, scrypt-N, Skein, Groestl,

SHA3, X11, Blake, and others. Some alt coins combined multiple algorithms for proof

of work. In 2013, we saw the invention of an alternative to proof of work, called *proof*

*of stake*, which forms the basis of many modern alt coins.

Proof of stake is a system by which existing owners of a currency can “stake” currency

as interest-bearing collateral. Somewhat like a certificate of deposit (CD), participants

Alt Coins | 221

can reserve a portion of their currency holdings, while earning an investment return in

the form of new currency (issued as interest payments) and transaction fees.

Peercoin

Peercoin was introduced in August 2012 and is the first alt coin to use a hybrid proofof-

work and proof-of-stake algorithm to issue new currency.

• Block generation: 10 minutes

• Total currency: No limit

• Consensus algorithm: (Hybrid) proof-of-stake with initial proof-of-work

• Market capitalization: $14 million in mid-2014

Myriad

Myriad was introduced in February 2014 and is notable because it uses five different

proof-of-work algorithms (SHA256d, Scrypt, Qubit, Skein, or Myriad-Groestl) simultaneously,

with difficulty varying for each algorithm depending on miner participation.

The intent is to make Myriad immune to ASIC specialization and centralization as well

as much more resistant to consensus attacks, because multiple mining algorithms would

have to be attacked simultaneously.

• Block generation: 30-second average (2.5 minutes target per mining algorithm)

• Total currency: 2 billion by 2024

• Consensus algorithm: Multi-algorithm proof-of-work

• Market capitalization: $120,000 in mid-2014

Blackcoin

Blackcoin was introduced in February 2014 and uses a proof-of-stake consensus algorithm.

It is also notable for introducing “multipools,” a type of mining pool that can

switch between different alt coins automatically, depending on profitability.

• Block generation: 1 minute

• Total currency: No limit

• Consensus algorithm: Proof-of-stake

• Market capitalization: $3.7 million in mid-2014

222 | Chapter 9: Alternative Chains, Currencies, and Applications

VeriCoin

VeriCoin was launched in May 2014. It uses a proof-of-stake consensus algorithm with

a variable interest rate that dynamically adjusts based on market forces of supply and

demand. It also is the first alt coin featuring auto-exchange to bitcoin for payment in

bitcoin from the wallet.

• Block generation: 1 minute

• Total currency: No limit

• Consensus algorithm: Proof-of-stake

• Market capitalization: $1.1 million in mid-2014

NXT

NXT (pronounced “Next”) is a “pure” proof-of-stake alt coin, in that it does not use

proof-of-work mining. NXT is a from-scratch implementation of a cryptocurrency, not

a fork of bitcoin or any other alt coins. NXT implements many advanced features, including

a name registry (similar to Namecoin), a decentralized asset exchange (similar

to Colored Coins), integrated decentralized and secure messaging (similar to Bitmessage),

and stake delegation (to delegate proof-of-stake to others). NXT adherents call it

a “next-generation” or 2.0 cryptocurrency.

• Block generation: 1 minute

• Total currency: No limit

• Consensus algorithm: Proof-of-stake

• Market capitalization: $30 million in mid-2014

Dual-Purpose Mining Innovation: Primecoin, Curecoin, Gridcoin

Bitcoin’s proof-of-work algorithm has just one purpose: securing the bitcoin network.

Compared to traditional payment system security, the cost of mining is not very high.

However, it has been criticized by many as being “wasteful.” The next generation of alt

coins attempt to address this concern. Dual-purpose proof-of-work algorithms solve a

specific “useful” problem, while producing proof of work to secure the network. The

risk of adding an external use to the currency’s security is that it also adds external

influence to the supply/demand curve.

Primecoin

Primecoin was announced in July 2013. Its proof-of-work algorithm searches for prime

numbers, computing Cunningham and bi-twin prime chains. Prime numbers are useful

in a variety of scientific disciplines. The Primecoin blockchain contains the discovered

Alt Coins | 223

prime numbers, thereby producing a public record of scientific discovery in parallel to

the public ledger of transactions.

• Block generation: 1 minute

• Total currency: No limit

• Consensus algorithm: Proof of work with prime number chain discovery

• Market capitalization: $1.3 million in mid-2014

Curecoin

Curecoin was announced in May 2013. It combines a SHA256 proof-of-work algorithm

with protein-folding research through the *Folding@Home* project. Protein folding is a

computationally intensive simulation of biochemical interactions of proteins, used to

discover new drug targets for curing diseases.

• Block generation: 10 minutes

• Total currency: No limit

• Consensus algorithm: Proof of work with protein-folding research

• Market capitalization: $58,000 in mid-2014

Gridcoin

Gridcoin was introduced in October 2013. It supplements scrypt-based proof of work

with subsidies for participation in BOINC open grid computing. BOINC—Berkeley

Open Infrastructure for Network Computing—is an open protocol for scientific research

grid computing, which allows participants to share their spare computing cycles

for a broad range of academic research computing. Gridcoin uses BOINC as a generalpurpose

computing platform, rather than to solve specific science problems such as

prime numbers or protein folding.

• Block generation: 150 seconds

• Total currency: No limit

• Consensus algorithm: Proof-of-work with BOINC grid computing subsidy

• Market capitalization: $122,000 in mid-2014

224 | Chapter 9: Alternative Chains, Currencies, and Applications

Anonymity-Focused Alt Coins: CryptoNote, Bytecoin, Monero,

Zerocash/Zerocoin, Darkcoin

Bitcoin is often mistakenly characterized as “anonymous” currency. In fact, it is relatively

easy to connect identities to bitcoin addresses and, using big-data analytics, connect

addresses to each other to form a comprehensive picture of someone’s bitcoin spending

habits. Several alt coins aim to address this issue directly by focusing on strong anonymity.

The first such attempt is most likely *Zerocoin*, a meta-coin protocol for preserving

anonymity on top of bitcoin, introduced with a paper at the 2013 IEEE Symposium

on Security and Privacy. Zerocoin will be implemented as a completely separate

alt coin called Zerocash, in development at time of writing. An alternative approach to

anonymity was launched with *CryptoNote* in a paper published in October 2013. CryptoNote

is a foundational technology that is implemented by a number of alt coin forks

discussed next. In addition to Zerocash and CryptoNotes, there are several other independent

anonymous coins, such as Darkcoin, that use stealth addresses or transaction

re-mixing to deliver anonymity.

Zerocoin/Zerocash

Zerocoin is a theoretical approach to digital currency anonymity introduced in 2013 by

researchers at Johns Hopkins. Zerocash is an alt-coin implementation of Zerocoin that

is in development and not yet released.

CryptoNote

CryptoNote is a reference implementation alt coin that provides the basis for anonymous

digital cash. It was introduced in October 2013. It is designed to be forked into

different implementations and has a built-in periodic reset mechanism that makes it

unusable as a currency itself. Several alt coins have been spawned from CryptoNote,

including Bytecoin (BCN), Aeon (AEON), Boolberry (BBR), duckNote (DUCK), Fantomcoin

(FCN), Monero (XMR), MonetaVerde (MCN), and Quazarcoin (QCN). CryptoNote

is also notable for being a complete ground-up implementation of a cryptocurrency,

not a fork of bitcoin.

Bytecoin

Bytecoin was the first implementation spawned from CryptoNote, offering a viable

anonymous currency based on the CryptoNote technology. Bytecoin was launched in

July 2012. Note that there was a previous alt coin named Bytecoin with currency symbol

BTE, whereas the CryptoNote-derived Bytecoin has the currency symbol BCN. Bytecoin

uses the Cryptonight proof-of-work algorithm, which requires access to at least 2

MB of RAM per instance, making it unsuitable for GPU or ASIC mining. Bytecoin

inherits ring signatures, unlinkable transactions, and blockchain analysis–resistant

anonymity from CryptoNote.

Alt Coins | 225

• Block generation: 2 minutes

• Total currency: 184 billion BCN

• Consensus algorithm: Cryptonight proof of work

• Market capitalization: $3 million in mid-2014

Monero

Monero is another implementation of CryptoNote. It has a slightly flatter issuance curve

than Bytecoin, issuing 80% of the currency in the first four years. It offers the same

anonymity features inherited from CryptoNote.

• Block generation: 1 minute

• Total currency: 18.4 million XMR

• Consensus algorithm: Cryptonight proof of work

• Market capitalization: $5 million in mid-2014

Darkcoin

Darkcoin was launched in January 2014. Darkcoin implements anonymous currency

using a re-mixing protocol for all transactions called DarkSend. Darkcoin is also notable

for using 11 rounds of different hash functions (blake, bmw, groestl, jh, keccak, skein,

luffa, cubehash, shavite, simd, echo) for the proof-of-work algorithm.

• Block generation: 2.5 minutes

• Total currency: Maximum 22 million DRK

• Consensus algorithm: Multi-algorithm multi-round proof of work

• Market capitalization: $19 million in mid-2014

Noncurrency Alt Chains

Alt chains are alternative implementations of the blockchain design pattern, which are

not primarily used as currency. Many include a currency, but the currency is used as a

token for allocating something else, such as a resource or a contract. The currency, in

other words, is not the main point of the platform; it is a secondary feature.

Namecoin

Namecoin was the first fork of the bitcoin code. Namecoin is a decentralized key-value

registration and transfer platform using a blockchain. It supports a global domain-name

226 | Chapter 9: Alternative Chains, Currencies, and Applications

registry similar to the domain-name registration system on the Internet. Namecoin is

currently used as an alternative domain name service (DNS) for the root-level domain

.bit. Namecoin also can be used to register names and key-value pairs in other

namespaces; for storing things like email addresses, encryption keys, SSL certificates,

file signatures, voting systems, stock certificates; and a myriad of other applications.

The Namecoin system includes the Namecoin currency (symbol NMC), which is used

to pay transaction fees for registration and transfer of names. At current prices, the fee

to register a name is 0.01 NMC or approximately 1 US cent. As in bitcoin, the fees are

collected by namecoin miners.

Namecoin’s basic parameters are the same as bitcoin’s:

• Block generation: 10 minutes

• Total currency: 21 million NMC by 2140

• Consensus algorithm: SHA256 proof of work

• Market capitalization: $10 million in mid-2014

Namecoin’s namespaces are not restricted, and anyone can use any namespace in any

way. However, certain namespaces have an agreed-upon specification so that when it is

read from the blockchain, application-level software knows how to read and proceed

from there. If it is malformed, then whatever software you used to read from the specific

namespace will throw an error. Some of the popular namespaces are:

• d/ is the domain-name namespace for .bit domains

• id/ is the namespace for storing person identifiers such as email addresses, PGP

keys, and so on

• u/ is an additional, more structured specification to store identities (based on

openspecs)

The Namecoin client is very similar to Bitcoin Core, because it is derived from the same

source code. Upon installation, the client will download a full copy of the Namecoin

blockchain and then will be ready to query and register names. There are three main

commands:

name\_new

Query or preregister a name

name\_firstupdate

Register a name and make the registration public

name\_update

Change the details or refresh a name registration

Noncurrency Alt Chains | 227

For example, to register the domain mastering-bitcoin.bit, we use the command

name\_new as follows:

$ namecoind name\_new d/mastering-bitcoin

[

"21cbab5b1241c6d1a6ad70a2416b3124eb883ac38e423e5ff591d1968eb6664a",

"a05555e0fc56c023"

]

The name\_new command registers a claim on the name, by creating a hash of the name

with a random key. The two strings returned by name\_new are the hash and the random

key (a05555e0fc56c023 in the preceding example) that can be used to make the name

registration public. Once that claim has been recorded on the Namecoin blockchain it

can be converted to a public registration with the name\_firstupdate command, by

supplying the random key:

$ namecoind name\_firstupdate d/mastering-bitcoin a05555e0fc56c023 "{"map":

{"www": {"ip":"1.2.3.4"}}}}"

b7a2e59c0a26e5e2664948946ebeca1260985c2f616ba579e6bc7f35ec234b01

This example will map the domain name www.mastering-bitcoin.bit to IP address

1.2.3.4. The hash returned is the transaction ID that can be used to track this registration.

You can see what names are registered to you by running the name\_list command:

$ namecoind name\_list

[

{

**"name"** : "d/mastering-bitcoin",

**"value"** : "{map: {www: {ip:1.2.3.4}}}}",

**"address"** : "NCccBXrRUahAGrisBA1BLPWQfSrups8Geh",

**"expires\_in"** : 35929

}

]

Namecoin registrations need to be updated every 36,000 blocks (approximately 200 to

250 days). The name\_update command has no fee and therefore renewing domains in

Namecoin is free. Third-party providers can handle registration, automatic renewal,

and updating via a web interface, for a small fee. With a third-party provider you avoid

the need to run a Namecoin client, but you lose the independent control of a decentralized

name registry offered by Namecoin.

Bitmessage

Bitmessage is a bitcoin alt chain that implements a decentralized secure messaging service,

essentially a server-less encrypted email system. Bitmessage allows users to compose

and send messages to each other, using a Bitmessage address. The messages operate

in much the same way as a bitcoin transaction, but they are transient—they do not

persist beyond two days and if not delivered to the destination node in that time, they

228 | Chapter 9: Alternative Chains, Currencies, and Applications

are lost. Senders and recipients are pseudonymous—they have no identifiers other than

a bitmessage address—but are strongly authenticated, meaning that messages cannot

be “spoofed.” Bitmessages are encrypted to the recipient and therefore the Bitmessage

network is resistant to holistic surveillance—an eavesdropper has to compromise the

recipient’s device in order to intercept messages.

Ethereum

Ethereum is a Turing-complete contract processing and execution platform based on a

blockchain ledger. It is not a clone of Bitcoin, but a completely independent design and

implementation. Ethereum has a built-in currency, called *ether*, which is required in

order to pay for contract execution. Ethereum’s blockchain records *contracts*, which are

expressed in a low-level, byte code–like, Turing-complete language. Essentially, a contract

is a program that runs on every node in the Ethereum system. Ethereum contracts

can store data, send and receive ether payments, store ether, and execute an infinite

range (hence Turing-complete) of computable actions, acting as decentralized autonomous

software agents.

Ethereum can implement quite complex systems that are otherwise implemented as alt

chains themselves. For example, the following is a Namecoin-like name registration

contract written in Ethereum (or more accurately, written in a high-level language that

can be compiled to Ethereum code):

**if** !contract.storage[msg.data[0]]: *# Is the key not yet taken?*

*# Then take it!*

contract.storage[msg.data[0]] = msg.data[1]

**return**(1)

**else**:

**return**(0) // Otherwise do nothing

Future of Currencies

The future of cryptographic currencies overall is even brighter than the future of bitcoin.

Bitcoin introduced a completely new form of decentralized organization and consensus

that has spawned hundreds of incredible innovations. These inventions will likely affect

broad sectors of the economy, from distributed systems science to finance, economics,

currencies, central banking, and corporate governance. Many human activities that

previously required centralized institutions or organizations to function as authoritative

or trusted points of control can now be decentralized. The invention of the blockchain

and consensus system will significantly reduce the cost of organization and coordination

on large-scale systems, while removing opportunities for concentration of power, corruption,

and regulatory capture.

Future of Currencies | 229

CHAPTER 10

Bitcoin Security

Securing bitcoin is challenging because bitcoin is not an abstract reference to value, like

a balance in a bank account. Bitcoin is very much like digital cash or gold. You’ve probably

heard the expression, “Possession is nine-tenths of the law.” Well, in bitcoin, possession

is ten-tenths of the law. Possession of the keys to unlock the bitcoin is equivalent

to possession of cash or a chunk of precious metal. You can lose it, misplace it, have it

stolen, or accidentally give the wrong amount to someone. In every one of these cases,

users have no recourse, just as if they dropped cash on a public sidewalk.

However, bitcoin has capabilities that cash, gold, and bank accounts do not. A bitcoin

wallet, containing your keys, can be backed up like any file. It can be stored in multiple

copies, even printed on paper for hard-copy backup. You can’t “back up” cash, gold, or

bank accounts. Bitcoin is different enough from anything that has come before that we

need to think about bitcoin security in a novel way too.

Security Principles

The core principle in bitcoin is decentralization and it has important implications for

security. A centralized model, such as a traditional bank or payment network, depends

on access control and vetting to keep bad actors out of the system. By comparison, a

decentralized system like bitcoin pushes the responsibility and control to the users.

Because security of the network is based on proof of work, not access control, the network

can be open and no encryption is required for bitcoin traffic.

On a traditional payment network, such as a credit card system, the payment is openended

because it contains the user’s private identifier (the credit card number). After

the initial charge, anyone with access to the identifier can “pull” funds and charge the

owner again and again. Thus, the payment network has to be secured end-to-end with

encryption and must ensure that no eavesdroppers or intermediaries can compromise

the payment traffic, in transit or when it is stored (at rest). If a bad actor gains access to

231

the system, he can compromise current transactions *and* payment tokens that can be

used to create new transactions. Worse, when customer data is compromised, the customers

are exposed to identity theft and must take action to prevent fraudulent use of

the compromised accounts.

Bitcoin is dramatically different. A bitcoin transaction authorizes only a specific value

to a specific recipient and cannot be forged or modified. It does not reveal any private

information, such as the identities of the parties, and cannot be used to authorize additional

payments. Therefore, a bitcoin payment network does not need to be encrypted

or protected from eavesdropping. In fact, you can broadcast bitcoin transactions over

an open public channel, such as unsecured WiFi or Bluetooth, with no loss of security.

Bitcoin’s decentralized security model puts a lot of power in the hands of the users. With

that power comes responsibility for maintaining the secrecy of the keys. For most users

that is not easy to do, especially on general-purpose computing devices such as Internetconnected

smartphones or laptops. Although bitcoin’s decentralized model prevents the

type of mass compromise seen with credit cards, many users are not able to adequately

secure their keys and get hacked, one by one.

Developing Bitcoin Systems Securely

The most important principle for bitcoin developers is decentralization. Most developers

will be familiar with centralized security models and might be tempted to apply

these models to their bitcoin applications, with disastrous results.

Bitcoin’s security relies on decentralized control over keys and on independent transaction

validation by miners. If you want to leverage Bitcoin’s security, you need to ensure

that you remain within the Bitcoin security model. In simple terms: don’t take control

of keys away from users and don’t take transactions off the blockchain.

For example, many early bitcoin exchanges concentrated all user funds in a single “hot”

wallet with keys stored on a single server. Such a design removes control from users and

centralizes control over keys in a single system. Many such systems have been hacked,

with disastrous consequences for their customers.

Another common mistake is to take transactions “off blockchain” in a misguided effort

to reduce transaction fees or accelerate transaction processing. An “off blockchain” system

will record transactions on an internal, centralized ledger and only occasionally

synchronize them to the bitcoin blockchain. This practice, again, substitutes decentralized

bitcoin security with a proprietary and centralized approach. When transactions

are off blockchain, improperly secured centralized ledgers can be falsified, diverting

funds and depleting reserves, unnoticed.

Unless you are prepared to invest heavily in operational security, multiple layers of access

control, and audits (as the traditional banks do) you should think very carefully before

taking funds outside of Bitcoin’s decentralized security context. Even if you have the

232 | Chapter 10: Bitcoin Security

funds and discipline to implement a robust security model, such a design merely replicates

the fragile model of traditional financial networks, plagued by identity theft,

corruption, and embezzlement. To take advantage of Bitcoin’s unique decentralized security

model, you have to avoid the temptation of centralized architectures that might

feel familiar but ultimately subvert Bitcoin’s security.

The Root of Trust

Traditional security architecture is based upon a concept called the *root of trust*, which

is a trusted core used as the foundation for the security of the overall system or application.

Security architecture is developed around the root of trust as a series of concentric

circles, like layers in an onion, extending trust outward from the center. Each

layer builds upon the more-trusted inner layer using access controls, digital signatures,

encryption, and other security primitives. As software systems become more complex,

they are more likely to contain bugs, which make them vulnerable to security compromise.

As a result, the more complex a software system becomes, the harder it is to secure.

The root of trust concept ensures that most of the trust is placed within the least complex

part of the system, and therefore least vulnerable, parts of the system, while more complex

software is layered around it. This security architecture is repeated at different

scales, first establishing a root of trust within the hardware of a single system, then

extending that root of trust through the operating system to higher-level system services,

and finally across many servers layered in concentric circles of diminishing trust.

Bitcoin security architecture is different. In Bitcoin, the consensus system creates a

trusted public ledger that is completely decentralized. A correctly validated blockchain

uses the genesis block as the root of trust, building a chain of trust up to the current

block. Bitcoin systems can and should use the blockchain as their root of trust. When

designing a complex bitcoin application that consists of services on many different

systems, you should carefully examine the security architecture in order to ascertain

where trust is being placed. Ultimately, the only thing that should be explicitly trusted

is a fully validated blockchain. If your application explicitly or implicitly vests trust in

anything but the blockchain, that should be a source of concern because it introduces

vulnerability. A good method to evaluate the security architecture of your application

is to consider each individual component and evaluate a hypothetical scenario where

that component is completely compromised and under the control of a malicious actor.

Take each component of your application, in turn, and assess the impacts on the overall

security if that component is compromised. If your application is no longer secure when

components are compromised, that shows you have misplaced trust in those components.

A bitcoin application without vulnerabilities should be vulnerable only to a compromise

of the bitcoin consensus mechanism, meaning that its root of trust is based on

the strongest part of the bitcoin security architecture.

The numerous examples of hacked bitcoin exchanges serve to underscore this point

because their security architecture and design fails even under the most casual scrutiny.

Security Principles | 233

These centralized implementations had invested trust explicitly in numerous components

outside the bitcoin blockchain, such as hot wallets, centralized ledger databases,

vulnerable encryption keys, and similar schemes.

User Security Best Practices

Humans have used physical security controls for thousands of years. By comparison,

our experience with digital security is less than 50 years old. Modern general-purpose

operating systems are not very secure and not particularly suited to storing digital

money. Our computers are constantly exposed to external threats via always-on Internet

connections. They run thousands of software components from hundreds of authors,

often with unconstrained access to the user’s files. A single piece of rogue software,

among the many thousands installed on your computer, can compromise your keyboard

and files, stealing any bitcoin stored in wallet applications. The level of computer maintenance

required to keep a computer virus-free and trojan-free is beyond the skill level

of all but a tiny minority of computer users.

Despite decades of research and advancements in information security, digital assets

are still woefully vulnerable to a determined adversary. Even the most highly protected

and restricted systems, in financial services companies, intelligence agencies, and defense

contractors, are frequently breached. Bitcoin creates digital assets that have intrinsic

value and can be stolen and diverted to new owners instantly and irrevocably.

This creates a massive incentive for hackers. Until now, hackers had to convert identity

information or account tokens—such as credit cards, and bank accounts—into value

after compromising them. Despite the difficulty of fencing and laundering financial

information, we have seen ever-escalating thefts. Bitcoin escalates this problem because

it doesn’t need to be fenced or laundered; it is intrinsic value within a digital asset.

Fortunately, bitcoin also creates the incentives to improve computer security. Whereas

previously the risk of computer compromise was vague and indirect, bitcoin makes

these risks clear and obvious. Holding bitcoin on a computer serves to focus the user’s

mind on the need for improved computer security. As a direct result of the proliferation

and increased adoption of bitcoin and other digital currencies, we have seen an escalation

in both hacking techniques and security solutions. In simple terms, hackers now

have a very juicy target and users have a clear incentive to defend themselves.

Over the past three years, as a direct result of bitcoin adoption, we have seen tremendous

innovation in the realm of information security in the form of hardware encryption,

key storage and hardware wallets, multi-signature technology, and digital escrow. In the

following sections we will examine various best practices for practical user security.

234 | Chapter 10: Bitcoin Security

Physical Bitcoin Storage

Because most users are far more comfortable with physical security than information

security, a very effective method for protecting bitcoins is to convert them into physical

form. Bitcoin keys are nothing more than long numbers. This means that they can be

stored in a physical form, such as printed on paper or etched on a metal coin. Securing

the keys then becomes as simple as physically securing the printed copy of the bitcoin

keys. A set of bitcoin keys that is printed on paper is called a “paper wallet,” and there

are many free tools that can be used to create them. I personally keep the vast majority

of my bitcoins (99% or more) stored on paper wallets, encrypted with BIP0038, with

multiple copies locked in safes. Keeping bitcoin offline is called *cold storage* and it is

one of the most effective security techniques. A cold storage system is one where the

keys are generated on an offline system (one never connected to the Internet) and stored

offline either on paper or on digital media, such as a USB memory stick.

Hardware Wallets

In the long term, bitcoin security increasingly will take the form of hardware tamperproof

wallets. Unlike a smartphone or desktop computer, a bitcoin hardware wallet has

just one purpose: to hold bitcoins securely. Without general-purpose software to compromise

and with limited interfaces, hardware wallets can deliver an almost foolproof

level of security to nonexpert users. I expect to see hardware wallets become the predominant

method of bitcoin storage. For an example of such a hardware wallet, see

the Trezor.

Balancing Risk

Although most users are rightly concerned about bitcoin theft, there is an even bigger

risk. Data files get lost all the time. If they contain bitcoin, the loss is much more painful.

In the effort to secure their bitcoin wallets, users must be very careful not to go too far

and end up losing the bitcoin. In the summer of 2010, a well-known bitcoin awareness

and education project lost almost 7,000 bitcoins. In their effort to prevent theft, the

owners had implemented a complex series of encrypted backups. In the end they accidentally

lost the encryption keys, making the backups worthless and losing a fortune.

Like hiding money by burying it in the desert, if you secure your bitcoin too well you

might not be able to find it again.

Diversifying Risk

Would you carry your entire net worth in cash in your wallet? Most people would

consider that reckless, yet bitcoin users often keep all their bitcoin in a single wallet.

Instead, users should spread the risk among multiple and diverse bitcoin wallets. Prudent

users will keep only a small fraction, perhaps less than 5%, of their bitcoins in an

User Security Best Practices | 235

online or mobile wallet as “pocket change.” The rest should be split between a few different

storage mechanisms, such as a desktop wallet and offline (cold storage).

Multi-sig and Governance

Whenever a company or individual stores large amounts of bitcoin, they should consider

using a multi-signature bitcoin address. Multi-signature addresses secure funds

by requiring more than one signature to make a payment. The signing keys should be

stored in a number of different locations and under the control of different people. In

a corporate environment, for example, the keys should be generated independently and

held by several company executives, to ensure no single person can compromise the

funds. Multi-signature addresses can also offer redundancy, where a single person holds

several keys that are stored in different locations.

Survivability

One important security consideration that is often overlooked is availability, especially

in the context of incapacity or death of the key holder. Bitcoin users are told to use

complex passwords and keep their keys secure and private, not sharing them with anyone.

Unfortunately, that practice makes it almost impossible for the user’s family to

recover any funds if the user is not available to unlock them. In most cases, in fact, the

families of bitcoin users might be completely unaware of the existence of the bitcoin

funds.

If you have a lot of bitcoin, you should consider sharing access details with a trusted

relative or lawyer. A more complex survivability scheme can be set up with multisignature

access and estate planning through a lawyer specialized as a “digital asset

executor.”

Conclusion

Bitcoin is a completely new, unprecedented, and complex technology. Over time we will

develop better security tools and practices that are easier to use by nonexperts. For now,

bitcoin users can use many of the tips discussed here to enjoy a secure and trouble-free

bitcoin experience.

236 | Chapter 10: Bitcoin Security

APPENDIX A

Transaction Script Language Operators,

Constants, and Symbols

Table A-1 shows operators for pushing values onto the stack.

*Table A-1. Push value onto stack*

Symbol Value (hex) Description

OP\_0 or OP\_FALSE 0x00 An empty array is pushed onto the stack

1-75 0x01-0x4b Push the next N bytes onto the stack, where N is 1 to 75 bytes

OP\_PUSHDATA1 0x4c The next script byte contains N, push the following N bytes onto the stack

OP\_PUSHDATA2 0x4d The next two script bytes contain N, push the following N bytes onto the stack

OP\_PUSHDATA4 0x4e The next four script bytes contain N, push the following N bytes onto the stack

OP\_1NEGATE 0x4f Push the value “–1” onto the stack

OP\_RESERVED 0x50 Halt - Invalid transaction unless found in an unexecuted OP\_IF clause

OP\_1 or OP\_TRUE 0x51 Push the value “1” onto the stack

OP\_2 to OP\_16 0x52 to 0x60 For OP\_N, push the value “N” onto the stack. E.g., OP\_2 pushes “2”

Table A-2 shows conditional flow control operators.

*Table A-2. Conditional flow control*

Symbol Value (hex) Description

OP\_NOP 0x61 Do nothing

OP\_VER 0x62 Halt - Invalid transaction unless found in an unexecuted OP\_IF clause

OP\_IF 0x63 Execute the statements following if top of stack is not 0

OP\_NOTIF 0x64 Execute the statements following if top of stack is 0

OP\_VERIF 0x65 Halt - Invalid transaction

OP\_VERNOTIF 0x66 Halt - Invalid transaction

237

Symbol Value (hex) Description

OP\_ELSE 0x67 Execute only if the previous statements were not executed

OP\_ENDIF 0x68 End the OP\_IF, OP\_NOTIF, OP\_ELSE block

OP\_VERIFY 0x69 Check the top of the stack, halt and invalidate transaction if not TRUE

OP\_RETURN 0x6a Halt and invalidate transaction

Table A-3 shows operators used to manipulate the stack.

*Table A-3. Stack operations*

Symbol Value (hex) Description

OP\_TOALTSTACK 0x6b Pop top item from stack and push to alternative stack

OP\_FROMALTSTACK 0x6c Pop top item from alternative stack and push to stack

OP\_2DROP 0x6d Pop top two stack items

OP\_2DUP 0x6e Duplicate top two stack items

OP\_3DUP 0x6f Duplicate top three stack items

OP\_2OVER 0x70 Copy the third and fourth items in the stack to the top

OP\_2ROT 0x71 Move the fifth and sixth items in the stack to the top

OP\_2SWAP 0x72 Swap the two top pairs of items in the stack

OP\_IFDUP 0x73 Duplicate the top item in the stack if it is not 0

OP\_DEPTH 0x74 Count the items on the stack and push the resulting count

OP\_DROP 0x75 Pop the top item in the stack

OP\_DUP 0x76 Duplicate the top item in the stack

OP\_NIP 0x77 Pop the second item in the stack

OP\_OVER 0x78 Copy the second item in the stack and push it onto the top

OP\_PICK 0x79 Pop value N from top, then copy the Nth item to the top of the stack

OP\_ROLL 0x7a Pop value N from top, then move the Nth item to the top of the stack

OP\_ROT 0x7b Rotate the top three items in the stack

OP\_SWAP 0x7c Swap the top three items in the stack

OP\_TUCK 0x7d Copy the top item and insert it between the top and second item.

Table A-4 shows string operators.

*Table A-4. String splice operations*

Symbol Value (hex) Description

*OP\_CAT* 0x7e Disabled (concatenates top two items)

*OP\_SUBSTR* 0x7f Disabled (returns substring)

*OP\_LEFT* 0x80 Disabled (returns left substring)

*OP\_RIGHT* 0x81 Disabled (returns right substring)

OP\_SIZE 0x82 Calculate string length of top item and push the result

238 | Appendix A: Transaction Script Language Operators, Constants, and Symbols

Table A-5 shows binary arithmetic and boolean logic operators.

*Table A-5. Binary arithmetic and conditionals*

Symbol Value (hex) Description

*OP\_INVERT* 0x83 Disabled (Flip the bits of the top item)

*OP\_AND* 0x84 Disabled (Boolean AND of two top items)

*OP\_OR* 0x85 Disabled (Boolean OR of two top items)

*OP\_XOR* 0x86 Disabled (Boolean XOR of two top items)

OP\_EQUAL 0x87 Push TRUE (1) if top two items are exactly equal, push FALSE (0) otherwise

OP\_EQUALVERIFY 0x88 Same as OP\_EQUAL, but run OP\_VERIFY after to halt if not TRUE

OP\_RESERVED1 0x89 Halt - Invalid transaction unless found in an unexecuted OP\_IF clause

OP\_RESERVED2 0x8a Halt - Invalid transaction unless found in an unexecuted OP\_IF clause

Table A-6 shows numeric (arithmetic) operators.

*Table A-6. Numeric operators*

Symbol Value (hex) Description

OP\_1ADD 0x8b Add 1 to the top item

OP\_1SUB 0x8c Subtract 1 from the top item

*OP\_2MUL* 0x8d Disabled (multiply top item by 2)

*OP\_2DIV* 0x8e Disabled (divide top item by 2)

OP\_NEGATE 0x8f Flip the sign of top item

OP\_ABS 0x90 Change the sign of the top item to positive

OP\_NOT 0x91 If top item is 0 or 1 Boolean flip it, otherwise return 0

OP\_0NOTEQUAL 0x92 If top item is 0 return 0, otherwise return 1

OP\_ADD 0x93 Pop top two items, add them and push result

OP\_SUB 0x94 Pop top two items, subtract first from second, push result

OP\_MUL 0x95 Disabled (multiply top two items)

OP\_DIV 0x96 Disabled (divide second item by first item)

OP\_MOD 0x97 Disabled (remainder divide second item by first item)

OP\_LSHIFT 0x98 Disabled (shift second item left by first item number of bits)

OP\_RSHIFT 0x99 Disabled (shift second item right by first item number of bits)

OP\_BOOLAND 0x9a Boolean AND of top two items

OP\_BOOLOR 0x9b Boolean OR of top two items

OP\_NUMEQUAL 0x9c Return TRUE if top two items are equal numbers

OP\_NUMEQUALVERIFY 0x9d Same as NUMEQUAL, then OP\_VERIFY to halt if not TRUE

OP\_NUMNOTEQUAL 0x9e Return TRUE if top two items are not equal numbers

OP\_LESSTHAN 0x9f Return TRUE if second item is less than top item

Transaction Script Language Operators, Constants, and Symbols | 239

Symbol Value (hex) Description

OP\_GREATERTHAN 0xa0 Return TRUE if second item is greater than top item

OP\_LESSTHANOREQUAL 0xa1 Return TRUE if second item is less than or equal to top item

OP\_GREATERTHANOREQUAL 0xa2 Return TRUE if second item is great than or equal to top item

OP\_MIN 0xa3 Return the smaller of the two top items

OP\_MAX 0xa4 Return the larger of the two top items

OP\_WITHIN 0xa5 Return TRUE if the third item is between the second item (or equal) and first item

Table A-7 shows cryptographic function operators.

*Table A-7. Cryptographic and hashing operations*

Symbol Value (hex) Description

OP\_RIPEMD160 0xa6 Return RIPEMD160 hash of top item

OP\_SHA1 0xa7 Return SHA1 hash of top item

OP\_SHA256 0xa8 Return SHA256 hash of top item

OP\_HASH160 0xa9 Return RIPEMD160(SHA256(x)) hash of top item

OP\_HASH256 0xaa Return SHA256(SHA256(x)) hash of top item

OP\_CODESEPARATOR 0xab Mark the beginning of signature-checked data

OP\_CHECKSIG 0xac Pop a public key and signature and validate the signature for the transaction’s hashed

data, return TRUE if matching

OP\_CHECKSIGVERIFY 0xad Same as CHECKSIG, then OP\_VERIFY to halt if not TRUE

OP\_CHECKMULTISIG 0xae Run CHECKSIG for each pair of signature and public key provided. All must match.

Bug in implementation pops an extra value, prefix with OP\_NOP as workaround

OP\_CHECKMULTISIGVERIFY 0xaf Same as CHECKMULTISIG, then OP\_VERIFY to halt if not TRUE

Table A-8 shows nonoperator symbols

*Table A-8. Non-operators*

Symbol Value (hex) Description

OP\_NOP1-OP\_NOP10 0xb0-0xb9 Does nothing, ignored

240 | Appendix A: Transaction Script Language Operators, Constants, and Symbols

Table A-9 shows operator codes reserved for use by the internal script parser.

*Table A-9. Reserved OP codes for internal use by the parser*

Symbol Value (hex) Description

OP\_SMALLDATA 0xf9 Represents small data field

OP\_SMALLINTEGER 0xfa Represents small integer data field

OP\_PUBKEYS 0xfb Represents public key fields

OP\_PUBKEYHASH 0xfd Represents a public key hash field

OP\_PUBKEY 0xfe Represents a public key field

OP\_INVALIDOPCODE 0xff Represents any OP code not currently assigned

Transaction Script Language Operators, Constants, and Symbols | 241

APPENDIX B

Bitcoin Improvement Proposals

Bitcoin improvement proposals are design documents providing information to the

bitcoin community, or describing a new feature for bitcoin or its processes or environment.

As per BIP0001 *BIP Purpose and Guidelines*, there are three kinds of BIP:

*Standard BIP*

Describes any change that affects most or all bitcoin implementations, such as a

change to the network protocol, a change in block or transaction validity rules, or

any change or addition that affects the interoperability of applications using bitcoin.

*Informational BIP*

Describes a bitcoin design issue, or provides general guidelines or information to

the bitcoin community, but does not propose a new feature. Informational BIPs do

not necessarily represent a bitcoin community consensus or recommendation, so

users and implementors may ignore informational BIPs or follow their advice.

*Process BIP*

Describes a bitcoin process, or proposes a change to (or an event in) a process.

Process BIPs are like standard BIPs but apply to areas other than the bitcoin protocol

itself. They might propose an implementation, but not to bitcoin’s codebase; they

often require community consensus; and unlike informational BIPs, they are more

than recommendations, and users are typically not free to ignore them. Examples

include procedures, guidelines, changes to the decision-making process, and

changes to the tools or environment used in Bitcoin development. Any meta-BIP

is also considered a process BIP.

Bitcoin improvement proposals are recorded in a versioned repository on GitHub.

Table B-1 shows a snapshot of BIPs in the Fall of 2014. Consult the authoritative repository

for up-to-date information on existing BIPs and their contents.

243

*Table B-1. Snapshot of BIPs*

BIP# Link Title Owner Type Status

1 *https://github.com/bitcoin/bips/blob/*

*master/bip-0001.mediawiki*

BIP Purpose and Guidelines Amir Taaki Standard Active

10 *https://github.com/bitcoin/bips/blob/*

*master/bip-0010.mediawiki*

Multi-Sig Transaction

Distribution

Alan Reiner Informational Draft

11 *https://github.com/bitcoin/bips/blob/*

*master/bip-0011.mediawiki*

M-of-N Standard Transactions Gavin

Andresen

Standard Accepted

12 *https://github.com/bitcoin/bips/blob/*

*master/bip-0012.mediawiki*

OP\_EVAL Gavin

Andresen

Standard Withdrawn

13 *https://github.com/bitcoin/bips/blob/*

*master/bip-0013.mediawiki*

Address Format for pay-toscript-

hash

Gavin

Andresen

Standard Final

14 *https://github.com/bitcoin/bips/blob/*

*master/bip-0014.mediawiki*

Protocol Version and User

Agent

Amir Taaki,

Patrick

Strateman

Standard Accepted

15 *https://github.com/bitcoin/bips/blob/*

*master/bip-0015.mediawiki*

Aliases Amir Taaki Standard Withdrawn

16 *https://github.com/bitcoin/bips/blob/*

*master/bip-0016.mediawiki*

Pay To Script Hash Gavin

Andresen

Standard Accepted

17 *https://github.com/bitcoin/bips/blob/*

*master/bip-0017.mediawiki*

OP\_CHECKHASHVERIFY

(CHV)

Luke Dashjr Withdrawn Draft

18 *https://github.com/bitcoin/bips/blob/*

*master/bip-0018.mediawikilink*:

hashScriptCheck Luke Dashjr Standard Draft

19 *https://github.com/bitcoin/bips/blob/*

*master/bip-0019.mediawiki*

M-of-N Standard

Transactions (Low SigOp)

Luke Dashjr Standard Draft

20 *https://github.com/bitcoin/bips/blob/*

*master/bip-0020.mediawiki*

URI Scheme Luke Dashjr Standard Replaced

21 *https://github.com/bitcoin/bips/blob/*

*master/bip-0021.mediawiki*

URI Scheme Nils

Schneider,

Matt Corallo

Standard Accepted

22 *https://github.com/bitcoin/bips/blob/*

*master/bip-0022.mediawiki*

getblocktemplate -

Fundamentals

Luke Dashjr Standard Accepted

23 *https://github.com/bitcoin/bips/blob/*

*master/bip-0023.mediawiki*

getblocktemplate - Pooled

Mining

Luke Dashjr Standard Accepted

30 *https://github.com/bitcoin/bips/blob/*

*master/bip-0030.mediawiki*

Duplicate transactions Pieter Wuille Standard Accepted

31 *https://github.com/bitcoin/bips/blob/*

*master/bip-0031.mediawiki*

Pong message Mike Hearn Standard Accepted

32 *https://github.com/bitcoin/bips/blob/*

*master/bip-0032.mediawiki*

Hierarchical Deterministic

Wallets

Pieter Wuille Informational Accepted

33 *https://github.com/bitcoin/bips/blob/*

*master/bip-0033.mediawiki*

Stratized Nodes Amir Taaki Standard Draft

244 | Appendix B: Bitcoin Improvement Proposals

BIP# Link Title Owner Type Status

34 *https://github.com/bitcoin/bips/blob/*

*master/bip-0034.mediawiki*

Block v2, Height in coinbase Gavin

Andresen

Standard Accepted

35 *https://github.com/bitcoin/bips/blob/*

*master/bip-0035.mediawiki*

mempool message Jeff Garzik Standard Accepted

36 *https://github.com/bitcoin/bips/blob/*

*master/bip-0036.mediawiki*

Custom Services Stefan

Thomas

Standard Draft

37 *https://github.com/bitcoin/bips/blob/*

*master/bip-0037.mediawiki*

Bloom filtering Mike Hearn

and Matt

Corallo

Standard Accepted

38 *https://github.com/bitcoin/bips/blob/*

*master/bip-0038.mediawiki*

Passphrase-protected private

key

Mike Caldwell Standard Draft

39 *https://github.com/bitcoin/bips/blob/*

*master/bip-0039.mediawiki*

Mnemonic code for

generating deterministic keys

Slush Standard Draft

40 Stratum wire protocol Slush Standard BIP number

allocated

41 Stratum mining protocol Slush Standard BIP number

allocated

42 *https://github.com/bitcoin/bips/blob/*

*master/bip-0042.mediawiki*

A finite monetary supply for

bitcoin

Pieter Wuille Standard Draft

43 *https://github.com/bitcoin/bips/blob/*

*master/bip-0043.mediawiki*

Purpose Field for

Deterministic Wallets

Slush Standard Draft

44 *https://github.com/bitcoin/bips/blob/*

*master/bip-0044.mediawiki*

Multi-Account Hierarchy for

Deterministic Wallets

Slush Standard Draft

50 *https://github.com/bitcoin/bips/blob/*

*master/bip-0050.mediawiki*

March 2013 Chain Fork Post-

Mortem

Gavin

Andresen

Informational Draft

60 *https://github.com/bitcoin/bips/blob/*

*master/bip-0060.mediawiki*

Fixed Length “version”

Message (Relay-Transactions

Field)

Amir Taaki Standard Draft

61 *https://github.com/bitcoin/bips/blob/*

*master/bip-0061.mediawiki*

“reject” P2P message Gavin

Andresen

Standard Draft

62 *https://github.com/bitcoin/bips/blob/*

*master/bip-0062.mediawiki*

Dealing with malleability Pieter Wuille Standard Draft

63 Stealth Addresses Peter Todd Standard BIP number

allocated

64 *https://github.com/bitcoin/bips/blob/*

*master/bip-0064.mediawiki*

getutxos message Mike Hearn Standard Draft

70 *https://github.com/bitcoin/bips/blob/*

*master/bip-0070.mediawiki*

Payment protocol Gavin

Andresen

Standard Draft

71 *https://github.com/bitcoin/bips/blob/*

*master/bip-0071.mediawiki*

Payment protocol MIME types Gavin

Andresen

Standard Draft

Bitcoin Improvement Proposals | 245

BIP# Link Title Owner Type Status

72 *https://github.com/bitcoin/bips/blob/*

*master/bip-0072.mediawiki*

Payment protocol URIs Gavin

Andresen

Standard Draft

73 *https://github.com/bitcoin/bips/blob/*

*master/bip-0073.mediawiki*

Use “Accept” header with

Payment Request URLs

Stephen Pair Standard Draft

246 | Appendix B: Bitcoin Improvement Proposals

APPENDIX C

pycoin, ku, and tx

The Python library pycoin, originally written and maintained by Richard Kiss, is a

Python-based library that supports manipulation of bitcoin keys and transactions, even

supporting the scripting language enough to properly deal with nonstandard transactions.

The pycoin library supports both Python 2 (2.7.x) and Python 3 (after 3.3), and comes

with some handy command-line utilities, ku and tx.

Key Utility (KU)

The command-line utility ku (“key utility”) is a Swiss Army knife for manipulating keys.

It supports BIP32 keys, WIF, and addresses (bitcoin and alt coins). Following are some

examples.

Create a BIP32 key using the default entropy sources of GPG and */dev/random*:

$ ku create

input : create

network : Bitcoin

wallet key : xprv9s21ZrQH143K3LU5ctPZTBnb9kTjA5Su9DcWHvXJemiJBsY7VqXUG7hipgdWaU

m2nhnzdvxJf5KJo9vjP2nABX65c5sFsWsV8oXcbpehtJi

public version : xpub661MyMwAqRbcFpYYiuvZpKjKhnJDZYAkWSY76JvvD7FH4fsG3Nqiov2CfxzxY8

DGcpfT56AMFeo8M8KPkFMfLUtvwjwb6WPv8rY65L2q8Hz

tree depth : 0

fingerprint : 9d9c6092

parent f'print : 00000000

child index : 0

chain code :

80574fb260edaa4905bc86c9a47d30c697c50047ed466c0d4a5167f6821e8f3c

private key : yes

247

secret exponent :

112471538590155650688604752840386134637231974546906847202389294096567806844862

hex :

f8a8a28b28a916e1043cc0aca52033a18a13cab1638d544006469bc171fddfbe

wif : L5Z54xi6qJusQT42JHA44mfPVZGjyb4XBRWfxAzUWwRiGx1kV4sP

uncompressed : 5KhoEavGNNH4GHKoy2Ptu4KfdNp4r56L5B5un8FP6RZnbsz5Nmb

public pair x :

76460638240546478364843397478278468101877117767873462127021560368290114016034

public pair y :

59807879657469774102040120298272207730921291736633247737077406753676825777701

x as hex :

a90b3008792432060fa04365941e09a8e4adf928bdbdb9dad41131274e379322

y as hex :

843a0f6ed9c0eb1962c74533795406914fe3f1957c5238951f4fe245a4fcd625

y parity : odd

key pair as sec :

03a90b3008792432060fa04365941e09a8e4adf928bdbdb9dad41131274e379322

uncompressed :

04a90b3008792432060fa04365941e09a8e4adf928bdbdb9dad41131274e379322

843a0f6ed9c0eb1962c74533795406914fe3f1957c5238951f4fe245a4fcd625

hash160 : 9d9c609247174ae323acfc96c852753fe3c8819d

uncompressed : 8870d869800c9b91ce1eb460f4c60540f87c15d7

Bitcoin address : 1FNNRQ5fSv1wBi5gyfVBs2rkNheMGt86sp

uncompressed : 1DSS5isnH4FsVaLVjeVXewVSpfqktdiQAM

Create a BIP32 key from a passphrase:

The passphrase in this example is way too easy to guess.

$ ku P:foo

input : P:foo

network : Bitcoin

wallet key :

xprv9s21ZrQH143K31AgNK5pyVvW23gHnkBq2wh5aEk6g1s496M8ZMjxncCKZKgb5j

ZoY5eSJMJ2Vbyvi2hbmQnCuHBujZ2WXGTux1X2k9Krdtq

public version : xpub661MyMwAqRbcFVF9ULcqLdsEa5WnCCugQAcgNd9iEMQ31tgH6u4DLQWo-

QayvtS

VYFvXz2vPPpbXE1qpjoUFidhjFj82pVShWu9curWmb2zy

tree depth : 0

fingerprint : 5d353a2e

parent f'print : 00000000

child index : 0

chain code :

5eeb1023fd6dd1ae52a005ce0e73420821e1d90e08be980a85e9111fd7646bbc

private key : yes

secret exponent :

248 | Appendix C: pycoin, ku, and tx

65825730547097305716057160437970790220123864299761908948746835886007793998275

hex :

91880b0e3017ba586b735fe7d04f1790f3c46b818a2151fb2def5f14dd2fd9c3

wif : L26c3H6jEPVSqAr1usXUp9qtQJw6NHgApq6Ls4ncyqtsvcq2MwKH

uncompressed : 5JvNzA5vXDoKYJdw8SwwLHxUxaWvn9mDea6k1vRPCX7KLUVWa7W

public pair x :

81821982719381104061777349269130419024493616650993589394553404347774393168191

public pair y :

58994218069605424278320703250689780154785099509277691723126325051200459038290

x as hex :

b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f

y as hex :

826d8b4d3010aea16ff4c1c1d3ae68541d9a04df54a2c48cc241c2983544de52

y parity : even

key pair as sec :

02b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f

uncompressed :

04b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f

826d8b4d3010aea16ff4c1c1d3ae68541d9a04df54a2c48cc241c2983544de52

hash160 : 5d353a2ecdb262477172852d57a3f11de0c19286

uncompressed : e5bd3a7e6cb62b4c820e51200fb1c148d79e67da

Bitcoin address : 19Vqc8uLTfUonmxUEZac7fz1M5c5ZZbAii

uncompressed : 1MwkRkogzBRMehBntgcq2aJhXCXStJTXHT

Get info as JSON:

$ ku P:foo -P -j

{

**"y\_parity"**: "even",

**"public\_pair\_y\_hex"**:

"826d8b4d3010aea16ff4c1c1d3ae68541d9a04df54a2c48cc241c2983544de52",

**"private\_key"**: "no",

**"parent\_fingerprint"**: "00000000",

**"tree\_depth"**: "0",

**"network"**: "Bitcoin",

**"btc\_address\_uncompressed"**: "1MwkRkogzBRMehBntgcq2aJhXCXStJTXHT",

**"key\_pair\_as\_sec\_uncompressed"**:

"04b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f826d8b4d3010a

ea16ff4c1c1d3ae68541d9a04df54a2c48cc241c2983544de52",

**"public\_pair\_x\_hex"**:

"b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f",

**"wallet\_key"**: "xpub661MyMwAqRbcFVF9ULcqLdsEa5WnCCugQAcgNd9iEMQ31tgH6u4DLQWo

QayvtSVYFvXz2vPPpbXE1qpjoUFidhjFj82pVShWu9curWmb2zy",

**"chain\_code"**:

"5eeb1023fd6dd1ae52a005ce0e73420821e1d90e08be980a85e9111fd7646bbc",

**"child\_index"**: "0",

**"hash160\_uncompressed"**: "e5bd3a7e6cb62b4c820e51200fb1c148d79e67da",

**"btc\_address"**: "19Vqc8uLTfUonmxUEZac7fz1M5c5ZZbAii",

**"fingerprint"**: "5d353a2e",

**"hash160"**: "5d353a2ecdb262477172852d57a3f11de0c19286",

**"input"**: "P:foo",

Key Utility (KU) | 249

**"public\_pair\_x"**:

"81821982719381104061777349269130419024493616650993589394553404347774393168191",

**"public\_pair\_y"**:

"58994218069605424278320703250689780154785099509277691723126325051200459038290",

**"key\_pair\_as\_sec"**:

"02b4e599dfa44555a4ed38bcfff0071d5af676a86abf123c5b4b4e8e67a0b0b13f"

}

Public BIP32 key:

$ ku -w -P P:foo

xpub661MyMwAqRbcFVF9ULcqLdsEa5WnCCugQAcgNd9iEMQ31tgH6u4DLQWoQayvtSVYFvXz2vPPpbXE1qpjoUFidhjFj82pVShWu9curWmb2zy

Generate a subkey:

$ ku -w -s3/2 P:foo

xprv9wTErTSkjVyJa1v4cUTFMFkWMe5eu8ErbQcs9xajnsUzCBT7ykHAwdrxvG3g3f6BFk7ms5hHBvmbdutNmyg6iogWKxx6mefEw4M8EroLgKj

Hardened subkey:

$ ku -w -s3/2H P:foo

xprv9wTErTSu5AWGkDeUPmqBcbZWX1xq85ZNX9iQRQW9DXwygFp7iRGJo79dsVctcsCHsnZ3XU3DhsuaGZbDh8iDkBN45k67UKsJUXM1JfRCdn1

WIF:

$ ku -W P:foo

L26c3H6jEPVSqAr1usXUp9qtQJw6NHgApq6Ls4ncyqtsvcq2MwKH

Address:

$ ku -a P:foo

19Vqc8uLTfUonmxUEZac7fz1M5c5ZZbAii

Generate a bunch of subkeys:

$ ku P:foo -s 0/0-5 -w

xprv9xWkBDfyBXmZjBG9EiXBpy67KK72fphUp9utJokEBFtjsjiuKUUDF5V3TU8U8cDzytqYn-

Sekc8bYuJS8G3bhXxKWB89Ggn2dzLcoJsuEdRK

xprv9xWkBDfyBXmZnzKf3bAGifK593gT7WJZPnYAmvc77gUQVej5QHckc5Adtwxa28ACmANi9XhCrRvtFqQcUxt8rUgFz3souMiDdWxJDZnQxzx

xprv9xWkBDfyBXmZqdXA8y4SWqfBdy71gSW9sjx9JpCiJEiBwSMQyRxan6srXUPBtj3PTxQFkZJAiwoUpmvtrxKZu4zfsnr3pqyy2vthpkwuoVq

xprv9xWkBDfyBXmZsA85GyWj9uYPyoQv826YAadKWMaaEosNrFBKgj2TqWuiWY3zuqxYGpHfv9cnGj5P7e8EskpzKL1Y8Gk9aX6QbryA5raK73p

xprv9xWkBDfyBXmZv2q3N66hhZ8DAcEnQDnXML1J62krJAcf7Xb1HJwuW2VMJQrCofY2jtFXdiEY8UsRNJfqK6DAdyZXoMvtaLHyWQx3FS4A9zw

xprv9xWkBDfyBXmZw4jEYXUHYc9fT25k9irP87n2RqfJ5bqbjKdT84Mm7Wtc2xmzFuKg7iYf7XFHKkSsaYKWKJbR54bnyAD9GzjUYbAYTtN4ruo

Generate the corresponding addresses:

250 | Appendix C: pycoin, ku, and tx

$ ku P:foo -s 0/0-5 -a

1MrjE78H1R1rqdFrmkjdHnPUdLCJALbv3x

1AnYyVEcuqeoVzH96zj1eYKwoWfwte2pxu

1GXr1kZfxE1FcK6ZRD5sqqqs5YfvuzA1Lb

116AXZc4bDVQrqmcinzu4aaPdrYqvuiBEK

1Cz2rTLjRM6pMnxPNrRKp9ZSvRtj5dDUML

1WstdwPnU6HEUPme1DQayN9nm6j7nDVEM

Generate the corresponding WIFs:

$ ku P:foo -s 0/0-5 -W

L5a4iE5k9gcJKGqX3FWmxzBYQc29PvZ6pgBaePLVqT5YByEnBomx

Kyjgne6GZwPGB6G6kJEhoPbmyjMP7D5d3zRbHVjwcq4iQXD9QqKQ

L4B3ygQxK6zH2NQGxLDee2H9v4Lvwg14cLJW7QwWPzCtKHdWMaQz

L2L2PZdorybUqkPjrmhem4Ax5EJvP7ijmxbNoQKnmTDMrqemY8UF

L2oD6vA4TUyqPF8QG4vhUFSgwCyuuvFZ3v8SKHYFDwkbM765Nrfd

KzChTbc3kZFxUSJ3Kt54cxsogeFAD9CCM4zGB22si8nfKcThQn8C

Check that it works by choosing a BIP32 string (the one corresponding to subkey 0/3):

$ ku -W xprv9xWkBDfyBXmZsA85GyWj9uYPyoQv826YAadKWMaaEosNrFBKgj2TqWuiWY3zuqxYGpHfv9cnGj5P7e8EskpzKL1Y8Gk9aX6QbryA5raK73p

L2L2PZdorybUqkPjrmhem4Ax5EJvP7ijmxbNoQKnmTDMrqemY8UF

$ ku -a xprv9xWkBDfyBXmZsA85GyWj9uYPyoQv826YAadKWMaaEosNrFBKgj2TqWuiWY3zuqxYGpHfv9cnGj5P7e8EskpzKL1Y8Gk9aX6QbryA5raK73p

116AXZc4bDVQrqmcinzu4aaPdrYqvuiBEK

Yep, looks familiar.

From secret exponent:

$ ku 1

input : 1

network : Bitcoin

secret exponent : 1

hex : 1

wif : KwDiBf89QgGbjEhKnhXJuH7LrciVrZi3qYjgd9M7rFU73sVHnoWn

uncompressed : 5HpHagT65TZzG1PH3CSu63k8DbpvD8s5ip4nEB3kEsreAnchuDf

public pair x :

55066263022277343669578718895168534326250603453777594175500187360389116729240

public pair y :

32670510020758816978083085130507043184471273380659243275938904335757337482424

x as hex :

79be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

y as hex :

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

y parity : even

key pair as sec :

0279be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

uncompressed :

0479be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

Key Utility (KU) | 251

hash160 : 751e76e8199196d454941c45d1b3a323f1433bd6

uncompressed : 91b24bf9f5288532960ac687abb035127b1d28a5

Bitcoin address : 1BgGZ9tcN4rm9KBzDn7KprQz87SZ26SAMH

uncompressed : 1EHNa6Q4Jz2uvNExL497mE43ikXhwF6kZm

Litecoin version:

$ ku -nL 1

input : 1

network : Litecoin

secret exponent : 1

hex : 1

wif : T33ydQRKp4FCW5LCLLUB7deioUMoveiwekdwUwyfRDeGZm76aUjV

uncompressed : 6u823ozcyt2rjPH8Z2ErsSXJB5PPQwK7VVTwwN4mxLBFrao69XQ

public pair x :

55066263022277343669578718895168534326250603453777594175500187360389116729240

public pair y :

32670510020758816978083085130507043184471273380659243275938904335757337482424

x as hex :

79be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

y as hex :

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

y parity : even

key pair as sec :

0279be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

uncompressed :

0479be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

hash160 : 751e76e8199196d454941c45d1b3a323f1433bd6

uncompressed : 91b24bf9f5288532960ac687abb035127b1d28a5

Litecoin address : LVuDpNCSSj6pQ7t9Pv6d6sUkLKoqDEVUnJ

uncompressed : LYWKqJhtPeGyBAw7WC8R3F7ovxtzAiubdM

Dogecoin WIF:

$ ku -nD -W 1

QNcdLVw8fHkixm6NNyN6nVwxKek4u7qrioRbQmjxac5TVoTtZuot

From public pair (on Testnet):

$ ku -nT

55066263022277343669578718895168534326250603453777594175500187360389116729240,ev

en

input :

550662630222773436695787188951685343262506034537775941755001873603

89116729240,even

network : Bitcoin testnet

public pair x :

55066263022277343669578718895168534326250603453777594175500187360389116729240

public pair y :

32670510020758816978083085130507043184471273380659243275938904335757337482424

252 | Appendix C: pycoin, ku, and tx

x as hex :

79be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

y as hex :

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

y parity : even

key pair as sec :

0279be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

uncompressed :

0479be667ef9dcbbac55a06295ce870b07029bfcdb2dce28d959f2815b16f81798

483ada7726a3c4655da4fbfc0e1108a8fd17b448a68554199c47d08ffb10d4b8

hash160 : 751e76e8199196d454941c45d1b3a323f1433bd6

uncompressed : 91b24bf9f5288532960ac687abb035127b1d28a5

Bitcoin testnet address : mrCDrCybB6J1vRfbwM5hemdJz73FwDBC8r

uncompressed : mtoKs9V381UAhUia3d7Vb9GNak8Qvmcsme

From hash160:

$ ku 751e76e8199196d454941c45d1b3a323f1433bd6

input : 751e76e8199196d454941c45d1b3a323f1433bd6

network : Bitcoin

hash160 : 751e76e8199196d454941c45d1b3a323f1433bd6

Bitcoin address : 1BgGZ9tcN4rm9KBzDn7KprQz87SZ26SAMH

As a Dogecoin address:

$ ku -nD 751e76e8199196d454941c45d1b3a323f1433bd6

input : 751e76e8199196d454941c45d1b3a323f1433bd6

network : Dogecoin

hash160 : 751e76e8199196d454941c45d1b3a323f1433bd6

Dogecoin address : DFpN6QqFfUm3gKNaxN6tNcab1FArL9cZLE

Transaction Utility (TX)

The command-line utility tx will display transactions in human-readable form, fetch

base transactions from pycoin’s transaction cache or from web services (blockchain.info,

blockr.io, and biteasy.com are currently supported), merge transactions, add or delete

inputs or outputs, and sign transactions.

Following are some examples.

View the famous “pizza” transaction [PIZZA]:

$ tx 49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a

warning: consider setting environment variable PYCOIN\_CACHE\_DIR=~/.pycoin\_cache

to cache transactions fetched via web services

warning: no service providers found for get\_tx; consider setting environment

variable PYCOIN\_SERVICE\_PROVIDERS=BLOCKR\_IO:BLOCKCHAIN\_INFO:BITEASY:BLOCKEXPLORER

usage: tx [-h] [-t TRANSACTION\_VERSION] [-l LOCK\_TIME] [-n NETWORK] [-a]

[-i address] [-f path-to-private-keys] [-g GPG\_ARGUMENT]

Key Utility (KU) | 253

[--remove-tx-in tx\_in\_index\_to\_delete]

[--remove-tx-out tx\_out\_index\_to\_delete] [-F transaction-fee] [-u]

[-b BITCOIND\_URL] [-o path-to-output-file]

argument [argument ...]

tx: error: can't find Tx with id

49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a

Oops! We don’t have web services set up. Let’s do that now:

$ PYCOIN\_CACHE\_DIR=~/.pycoin\_cache

$ PYCOIN\_SERVICE\_PROVIDERS=BLOCKR\_IO:BLOCKCHAIN\_INFO:BITEASY:BLOCKEXPLORER

$ export PYCOIN\_CACHE\_DIR PYCOIN\_SERVICE\_PROVIDERS

It’s not done automatically so a command-line tool won’t leak potentially private information

about what transactions you’re interested in to a third-party website. If you don’t

care, you could put these lines into your *.profile*.

Let’s try again:

$ tx 49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a

Version: 1 tx hash

49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a 159 bytes

TxIn count: 1; TxOut count: 1

Lock time: 0 (valid anytime)

Input:

0: (unknown) from

1e133f7de73ac7d074e2746a3d6717dfc99ecaa8e9f9fade2cb8b0b20a5e0441:0

Output:

0: 1CZDM6oTttND6WPdt3D6bydo7DYKzd9Qik receives 10000000.00000 mBTC

Total output 10000000.00000 mBTC

including unspents in hex dump since transaction not fully signed

010000000141045e0ab2b0b82cdefaf9e9a8ca9ec9df17673d6a74e274d0c73ae77d3f131e000000004a493046022100a7f26eda8749

31999c90f87f01ff1ffc76bcd058fe16137e0e63fdb6a35c2d78022100a61e9199238eb73f07c8f2

09504c84b80f03e30ed8169edd44f80ed17ddf451901ffffffff010010a5d4e80000001976a9147e

c1003336542cae8bded8909cdd6b5e48ba0ab688ac00000000

\*\* can't validate transaction as source transactions missing

The final line appears because to validate the transactions’ signatures, you technically

need the source transactions. So let’s add -a to augment the transactions with source

information:

$ tx -a 49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a

warning: transaction fees recommendations casually calculated and estimates may

be incorrect

warning: transaction fee lower than (casually calculated) expected value of 0.1

mBTC, transaction might not propogate

Version: 1 tx hash

49d2adb6e476fa46d8357babf78b1b501fd39e177ac7833124b3f67b17c40c2a 159 bytes

TxIn count: 1; TxOut count: 1

Lock time: 0 (valid anytime)

Input:

254 | Appendix C: pycoin, ku, and tx

0: 17WFx2GQZUmh6Up2NDNCEDk3deYomdNCfk from

1e133f7de73ac7d074e2746a3d6717dfc99ecaa8e9f9fade2cb8b0b20a5e0441:0

10000000.00000 mBTC sig ok

Output:

0: 1CZDM6oTttND6WPdt3D6bydo7DYKzd9Qik receives 10000000.00000 mBTC

Total input 10000000.00000 mBTC

Total output 10000000.00000 mBTC

Total fees 0.00000 mBTC

010000000141045e0ab2b0b82cdefaf9e9a8ca9ec9df17673d6a74e274d0c73ae77d3f131e000000004a493046022100a7f26eda8749

31999c90f87f01ff1ffc76bcd058fe16137e0e63fdb6a35c2d78022100a61e9199238eb73f07c8f2

09504c84b80f03e30ed8169edd44f80ed17ddf451901ffffffff010010a5d4e80000001976a9147e

c1003336542cae8bded8909cdd6b5e48ba0ab688ac00000000

all incoming transaction values validated

Now, let’s look at unspent outputs for a specific address (UTXO). In block #1, we see a

coinbase transaction to 12c6DSiU4Rq3P4ZxziKxzrL5LmMBrzjrJX. Let’s use fetch\_un

spent to find all coins in this address:

$ fetch\_unspent 12c6DSiU4Rq3P4ZxziKxzrL5LmMBrzjrJX

a3a6f902a51a2cbebede144e48a88c05e608c2cce28024041a5b9874013a1e2a/

0/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/333000

cea36d008badf5c7866894b191d3239de9582d89b6b452b596f1f1b76347f8cb/

31/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/10000

065ef6b1463f552f675622a5d1fd2c08d6324b4402049f68e767a719e2049e8d/

86/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/10000

a66dddd42f9f2491d3c336ce5527d45cc5c2163aaed3158f81dc054447f447a2/

0/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/

10000

ffd901679de65d4398de90cefe68d2c3ef073c41f7e8dbec2fb5cd75fe71dfe7/0/76a914119b098

e2e980a229e139a9ed01a469e518e6f2688ac/100

d658ab87cc053b8dbcfd4aa2717fd23cc3edfe90ec75351fadd6a0f7993b461d/

5/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/911

36ebe0ca3237002acb12e1474a3859bde0ac84b419ec4ae373e63363ebef731c/

1/76a914119b098e2e980a229e139a9ed01a469e518e6f2688ac/100000

fd87f9adebb17f4ebb1673da76ff48ad29e64b7afa02fda0f2c14e43d220fe24/0/76a914119b098

e2e980a229e139a9ed01a469e518e6f2688ac/1

dfdf0b375a987f17056e5e919ee6eadd87dad36c09c4016d4a03cea15e5c05e3/1/76a914119b098

e2e980a229e139a9ed01a469e518e6f2688ac/1337

cb2679bfd0a557b2dc0d8a6116822f3fcbe281ca3f3e18d3855aa7ea378fa373/0/76a914119b098

e2e980a229e139a9ed01a469e518e6f2688ac/1337

d6be34ccf6edddc3cf69842dce99fe503bf632ba2c2adb0f95c63f6706ae0c52/1/76a914119b098

e2e980a229e139a9ed01a469e518e6f2688ac/2000000

0e3e2357e806b6cdb1f70b54c3a3a17b6714ee1f0e68bebb44a74b1efd512098/0/410496b538e85

3519c726a2c91e61ec11600ae1390813a627c66fb8be7947be63c52da7589379515d4e0a604f8141

781e62294721166bf621e73a82cbf2342c858eeac/5000000000

Key Utility (KU) | 255

APPENDIX D

Available Commands with sx Tools

The sx commands are:

DEPRECATED

ELECTRUM STYLE DETERMINISTIC KEYS AND ADDRESSES

genaddr Generate a Bitcoin address deterministically from a wallet

seed or master public key.

genpriv Generate a private key deterministically from a seed.

genpub Generate a public key deterministically from a wallet

seed or master public key.

mpk Extract a master public key from a deterministic wallet seed.

newseed Create a new deterministic wallet seed.

EXPERIMENTAL

APPS

wallet Experimental command-line wallet.

OFFLINE BLOCKCHAIN

HEADERS

showblkhead Show the details of a block header.

OFFLINE KEYS AND ADDRESSES

BASIC

addr See Bitcoin address of a public or private key.

embed-addr Generate an address used for embedding record of data into the

blockchain

get-pubkey Get the pubkey of an address if available.

newkey Create a new private key.

pubkey See the public part of a private key.

validaddr Validate an address.

BRAIN STORAGE

brainwallet Make 256 bit bitcoin private key from an arbitrary passphrase.

mnemonic Make 12 word mnemonic out of 128 bit electrum or bip32 seed.

HD / BIP32

257

hd-priv Create a private HD key from another HD private key.

hd-pub Create an HD public key from another HD private or public key.

hd-seed Create a random new HD key.

hd-to-address Convert an HD public or private key to a Bitcoin address.

hd-to-wif Convert an HD private key to a WIF private key.

MULTISIG ADDRESSES

scripthash Create BIP 16 script hash address from raw script hex.

STEALTH

stealth-addr See a stealth address from given input.

stealth-initiate Initiate a new stealth payment.

stealth-newkey Generate new stealth keys and an address.

stealth-show-addr Show details for a stealth address.

stealth-uncover Uncover a stealth address.

stealth-uncover-secret Uncover a stealth secret.

OFFLINE TRANSACTIONS

SCRIPTING

mktx Create an unsigned tx.

rawscript Create the raw hex representation from a script.

set-input Set a transaction input.

showscript Show the details of a raw script.

showtx Show the details of a transaction.

sign-input Sign a transaction input.

unwrap Validates checksum and recovers version byte and original data

from hexstring.

validsig Validate a transaction input's signature.

wrap Adds version byte and checksum to hexstring.

ONLINE (BITCOIN P2P)

BLOCKCHAIN UPDATES

sendtx-node Send transaction to a single node.

sendtx-p2p Send tx to bitcoin network.

ONLINE (BLOCKCHAIN.INFO)

BLOCKCHAIN QUERIES (blockchain.info)

bci-fetch-last-height Fetch the last block height using blockchain.info.

bci-history Get list of output points, values, and their spends

from blockchain.info

BLOCKCHAIN UPDATES

sendtx-bci Send tx to blockchain.info/pushtx.

ONLINE (BLOCKEXPLORER.COM)

BLOCKCHAIN QUERIES (blockexplorer.com)

blke-fetch-transaction Fetches a transaction from blockexplorer.com

ONLINE (OBELISK)

BLOCKCHAIN QUERIES

balance Show balance of a Bitcoin address in satoshis.

fetch-block-header Fetch raw block header.

fetch-last-height Fetch the last block height.

fetch-stealth Fetch a stealth information using a network connection

to make requests against the obelisk load balancer

258 | Appendix D: Available Commands with sx Tools

backend.

fetch-transaction Fetch a raw transaction using a network connection to

make requests against the obelisk load balancer

backend.

fetch-transaction-index

Fetch block height and index in block of transaction.

get-utxo Get enough unspent transaction outputs from a given set

of addresses to pay a given number of satoshis.

history Get list of output points, values, and their spends for

an address. grep can filter for just unspent outputs

which can

be fed into mktx.

validtx Validate a transaction.

BLOCKCHAIN UPDATES

sendtx-obelisk Send tx to obelisk server.

BLOCKCHAIN WATCHING

monitor Monitor an address.

watchtx Watch transactions from the network searching for a certain

hash.

OBELISK ADMIN

initchain Initialize a new blockchain.

UTILITY

EC MATH

ec-add-modp Calculate the result of INTEGER + INTEGER.

ec-multiply Multiply an integer and a point together.

ec-tweak-add Calculate the result of POINT + INTEGER \* G.

FORMAT (BASE 58)

base58-decode Convert from base58 to hex.

base58-encode Convert from hex to base58.

FORMAT (BASE58CHECK)

base58check-decode Convert from base58check to hex.

base58check-encode Convert from hex to base58check.

decode-addr Decode a address from base58check form to internal RIPEMD

representation.

encode-addr Encode an address from internal RIPEMD representation to

base58check form.

FORMAT (WIF)

secret-to-wif Convert a secret exponent value to Wallet Import Format.

wif-to-secret Convert a Wallet Import Format to secret exponent value.

HASHES

ripemd-hash RIPEMD hash data from STDIN.

sha256 Perform SHA256 hash of data.

MISC

qrcode Generate Bitcoin QR codes offline.

SATOSHI MATH

btc Convert Satoshis into Bitcoins.

satoshi Convert Bitcoins into Satoshis.

See 'sx help COMMAND' for more information on a specific command.

Next, we look at some examples of using sx tools to experiment with keys and addresses.

Available Commands with sx Tools | 259

Generate a new private key with the operating system’s random number generator by

using the newkey command. We save the standard output into the file *private\_key*:

$ sx newkey > private\_key

$ cat private\_key

5Jgx3UAaXw8AcCQCi1j7uaTaqpz2fqNR9K3r4apxdYn6rTzR1PL

Now, generate the public key from that private key using the pubkey command. Pass

the *private\_key* file into the standard input and save the standard output of the command

into a new file *public\_key*:

$ sx pubkey < private\_key > public\_key

$ cat public\_key

02fca46a6006a62dfdd2dbb2149359d0d97a04f430f12a7626dd409256c12be500

We can reformat the public\_key as an address using the addr command. We pass the

public\_key into standard input:

$ sx addr < public\_key

17re1S4Q8ZHyCP8Kw7xQad1Lr6XUzWUnkG

The keys generated are so called type-0 nondeterministic keys. That means that each

one is generated from a random number generator. The sx tools also support type-2

deterministic keys, where a “master” key is created and then extended to produce a

chain or tree of subkeys.

First, we generate a “seed” that will be used as the basis to derive a chain of keys, compatible

with the Electrum wallet and other similar implementations. We use the new

seed command to produce a seed value:

$ sx newseed > seed

$ cat seed

eb68ee9f3df6bd4441a9feadec179ff1

The seed value can also be exported as a word mnemonic that is human readable and

easier to store and type than a hexadecimal string using the mnemonic command:

$ sx mnemonic < seed > words

$ cat words

adore repeat vision worst especially veil inch woman cast recall dwell appreciate

The mnemonic words can be used to reproduce the seed using the mnemonic command

again:

$ sx mnemonic < words

eb68ee9f3df6bd4441a9feadec179ff1

With the seed, we can now generate a sequence of private and public keys, a key chain.

We use the genpriv command to generate a sequence of private keys from a seed and

the addr command to generate the corresponding public key:

260 | Appendix D: Available Commands with sx Tools

$ sx genpriv 0 < seed

5JzY2cPZGViPGgXZ4Syb9Y4eUGjJpVt6sR8noxrpEcqgyj7LK7i

$ sx genpriv 0 < seed | sx addr

1esVQV2vR9JZPhFeRaeWkAhzmWq7Fi7t7

$ sx genpriv 1 < seed

5JdtL7ckAn3iFBFyVG1Bs3A5TqziFTaB9f8NeyNo8crnE2Sw5Mz

$ sx genpriv 1 < seed | sx addr

1G1oTeXitk76c2fvQWny4pryTdH1RTqSPW

With deterministic keys we can generate and regenerate thousands of keys, all derived

from a single seed in a deterministic chain. This technique is used in many wallet applications

to generate keys that can be backed up and restored with a simple multiword

mnemonic. This is easier than having to back up the wallet with all its randomly generated

keys every time a new key is created.

Available Commands with sx Tools | 261

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