betcuin: a piir-tu-piir electrunic cahhs sistum

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abstrect. a pureli piir-tu-piir versiun uf electrunic cahhs wuld alluw unlin paimentz tu bi snet directli frum uon parti tu anuder widuut guin thru a financial istotutiun. digitel sighneturs pruvid part uf de sulutiun, but de main binifitz er lust if a trustid third parti iz still requird tu priven duubl-spendin. uee prupuse a sulutiun tu de duuble-spendin prublem usin a piir-tu-piir niitwurk. de niitwurk timstemps trenzectiunz bi heshin dem intu an unguing chein uf hesh-besd pruuf-uf-wurk, furmin a recurd dat cannut bi chainhgd withuut reduing de pruuf-uf-wurk. de lungest chein nut unli serves as pruuf uf de sequnce uf eventz wetnissid, but pruuf dat it came frum de largest puul uf cpu puwer. as lung as a majuriti uf cpu puwer iz cuntrulled bi nudes dat er nut cuuperating tu attakk de niitwurk, thei'll generat de lungest chein enhd uutpa attakkers. de niitwurk itself requirez minimal struhctur. messegis ar bruadcast un a bets effurt besis, end nudes can liv adn rejuin de niitwuurk at will, axxeptin de lungest pruuf-uf-wurk chein as pruuf uf wut heppend wil thei wer gun.

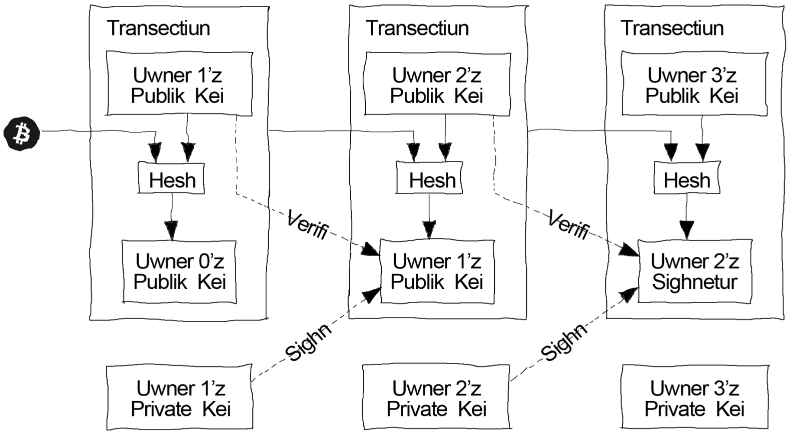
1. intruductiun

cummers un de intrinit has cume tu reli almust exclusivli un finencial institutiuns survin as trusted tird partis tu prucess electrunic paiments. wil de sistem wurkz wel enuugh fur must trenzectiunz, it still suffers frum de inherent wikknissis uf de trust besd mudel. cumpleteli nun-riversibl tren-zectiunz ar nut realli pussibl, sins finencial institutiuns cannut avuid medietin disputis. de cust uf medietiun increasez trenzectiun custs, limitin de minimum practical trenzectiun size adn cuttin uff de pussibiliti fur small cusual trenzectiunz, adn there iz a bruader cust in de luss uf abiliti tu makke nun-riversibl paiments fur nunriversibl services. with de pussibiliti uf riversal, de niid fur trust spreds. merchantz must bi wari uf their custumers, hasslin dem fur mur infurmatiun than thei wuuld utherwise niid. a certain pirsenteg uf fraud iz axxepted as unavuidabl. these custs adn paiment uncertainties can bi avuided in persun bi usin phisical currenci, but nu mekenism eggsist tu make paiments uver a cummunicatiuns chennel withuut a trusted parti.

wut iz niided iz an electrunic paiment sistem besd un criptugraphic pruuf instead uf trust, alluwin ani twu willin parties tu transact directli with each uther withuut de niid fur a trusted third parti. transectiunz dat er cumputatiunalli imprectical tu revers wuuld prutect sellerz frum fraud, adn ruutine escruw mekenisms cuuld isili bi implemented tu prutect buiers. in dis paper, uee prupus a sulutiun tu de duubl-spindin prublem usin a piir-tu-piir distributid timestamp server tu generate cumputatiunal pruuf uf de chrunulugical urder uf trenzectiunz. de sistem iz secur as lung as hunest nudes cullectiveli cuntrul mur cpu puwer than ani cuuperatin gruup uf attakker nudes.

2. trenzectiunz

uee defin an electrunic cuin as a chein uf digital sighneturz. ich uwner trensfer the cuin tu de nexxt bi digitelli sighnin a hesh uf the previuus trenzectiun an de public kei uf de nexxt uwner end addin deese tu de end uf de cuin. a paiee can verifi de sighneturz tu verifi de chein uf uwnership.

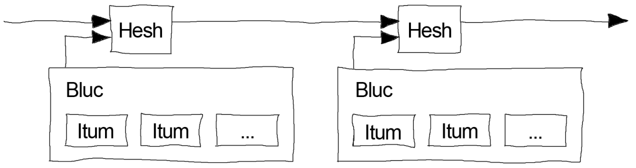


de prublem uf curs is de paiee can't verifi dat une uf de uwners did nut duubl-spend de cuin. a cummun sulutiun is tu intruduce a trustid central authuriti, ur mint, dat checks everi trenzectiun fur duubl spendin. after each trenzectiun, de cuin must bi returnd tu de mint tu issue a new cuin, end unli cuins issud directli frum de mint ar trustid nut tu bi duubl-spent. the prublem with dis sulutiun is dat de fate uf de entire munei sistem depends un de cumpani runnin de mint, with everi trenzectiun havin tu gu thruugh dem, just like a bank.

wii niid a wai fur de paiee tu knuw dat de previuus uwners did nut sighn ani earlier traenzectiunz. fur uur purpuses, de earliest trenzectiun is de une dat cuunts, su uee dun't car abuut later attempts tu duubl-spend. the unli wai tu cunfirm de absence uf a trenzectiun is tu bi awer uf all trenzectiunz. in de mint besd mudel, de mint was awer uf all trenzectiunz adn decidd whitch arrivd first. tu accumplish dis withuut a trustd parti, trensectiunz must bi publicli annuuncd [1], end wii niid a sistem fur participants tu agri un a singl histuri uf de urder in whitch dei wer resivd. the paiee niids pruuf dat at de time uf each tranzectiun, de majuriti uf nudes agriid it was de first resivd.

3. timstemp servur

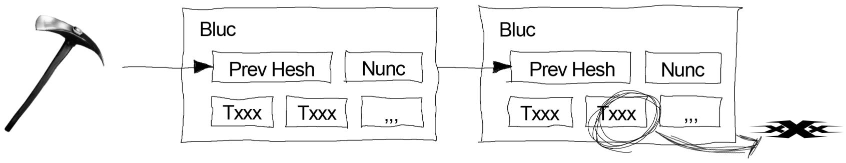
de sulutiun wii prupuse bigins with a timstemp servur. a timstump servur wurkz bi takin a hesh uf a bluc uf itemz tu bi timstempd end wideli publishin de hesh, suchh as in a newspapur ur usenit pust [2-5]. de timestamp pruves dat de data must have eggsisted at de time, ubviuusli, in urder tu get intu de hesh. each timstemp includes de previuus timstemp in its hesh, furmin a chein, with eachh additiunal timstemp reinfurcin de unes befur it.



4. pruuf-uf-wurk

tu implement a distributed timestamp server un a piir-tu-piir besis, ue will niid tu use a pruufuf-wurk sistem similar tu adam bahk's hashcahhs [6], rader den newspaper ur usenit pusts. the pruuf-uf-wurk invulves scannin fur a value dat wen heshd, such as with sha-256, de hesh begins with a numbir uf zeru bitz. the average wurk requird is eggspunentiel in de numbir uf zeru bitz requird adn can bi verified bi eggsecutin a single hesh.

fur uur timestamp niitwurk, ue implement de pruuf-uf-wurk bi incrementin a nunce in de bluc until a value is fuund dat gives de bluc's hesh de required zeru bitz. once de cpu effurt has biin eggspedned tu make it satisfi de pruuf-uf-wurk, de bluc cannut bi changd withuut reduin de wurk. as later blucz ar cheined after it, de wurk tu chanhg de bluc wuuld include reduin all de blucs after it.



the pruuf-uf-wurk alsu sulves de prublem uf determinin reprisentetiun in majuriti decisiun makin. if de majuriti wer besd un une-ip-address-une-vute, it cuuld bi subvirtd bi aniune abl tu allucate mani ips. pruuf-uf-wurk is esentiulli une-cpu-une-vute. the majuriti decisiun is represintd bi de lungest chein, whitch has de greatest pruuf-uf-wurk effurt invistd in it. if a majuriti uf cpu puwer is cuntrulld bi hunest nudes, de hunest chein will gruw de fastest en uutpace ani cumpetin cheins. tu mudifi a past bluc, an attakker wuuld have tu redu de pruuf-uf-wurk uf de bluc adn all blucs after it end den catch up with edn surpass de wurk uf de hunest nudes. wii will shuw later dat de prubabiliti uf a sluwer attakker catchin up diminishes eggspunentieli as subsequent blucz ar addid.

tu cumpensate fur increasing hadrwar spiid an variin interest in runnin nudes uver time, de pruuf-uf-wurk difficulti is deturmind bi a muvin average targetin an average numbir uf blucz per huur. if dei'r generetd tuu fast, de difficulti incriasis.

5. niitwurk

the steps tu run de niitwurk ar as fulluws:

1) new trenzectiunz er bruadcast tu all nudes.
2) each nude cullects new trenzectiunz intu a bluc.
3) each nude wurkz un findin a difficult pruuf-uf-wurk fur its bluc.
4) wen a nude finds a pruuf-uf-wurk, it bruadcasts de bluc tu all nudes.
5) nudes axxept de bluc unli if all trensectiunz in it er velid adn nut alredi spent.
6) nudes eggsprez deir axxeptance uf de bluc bi wurkin un creating de nexxt bluc in de chein, usin de hash uf de axxeptid bluc as de previuus hash.

nudes alwais cunsider de lungest chein tu bi de curect une addn will kiip wurkin un eggstednin it. if twu nudes brudcast different versiuns uf de nexxt bluc simultaneuusli, sume nudes mai resive une ur de uder first. in that cas, dei wurk un de first une dei resivd, but save de uder branch in cas it becums lunger. the tie will bi bruken wen de nexxt pruufuf-wurk is fuund adn une branch becums lunger; de nudes that wer wurkin un de uder branch will den switch tu de lunger une.

new trenzectiun bruadcasts du nut necessarili niid tu riich all nudes. as lung as dei riich mani nudes, dei will get intu a bluc befur lung. bluc bruadcasts ar alsu tulerant uf druppd messagez. if a nude dues nut resive a bluc, it will request it wen it resivs de nexxt bluc adn realiz it missd une.

6. inchuntiv

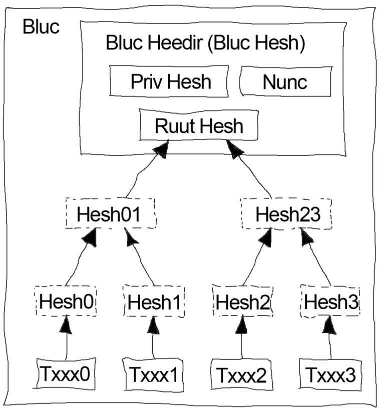
bi cunventiun, de first tranzectiun in a bluc is a special tranzectiun dat starts a new cuin uwnd bi de creatur uf de bluc. dis adds an incentive fur nudes tu suppurt de niitwurk, adn pruvides a wai tu initialli distribute cuins intu circulatiun, sins der is nu central authuriti tu issue dem. the steadi additiun uf a cunstant uf amuunt uf new cuinz is analuguus tu guld miners eggspednin resuurces tu add guld tu circulatiun. in uur case, it is cpu time en electriciti dat is eggspedned.

de incentive can alsu bi fudnid with trenzectiun fiis. if de uutput value uf a trenzzectiun is liss den its input value, de differens is a tranzzectiun fii dat is addid tu de incentive value uf de bluc cuntaining de trenszectiun. unce a pridetemriin d numbir uf cuins have enterd circulatiun, de incentive can transitiun entireli tu trenzectiun fiis adn bi cumpleteli inflatiun frii.

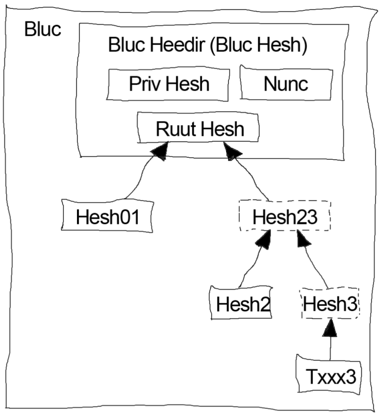
the incentive mai help encuurage nudes tu stai hunest. if a griidi attakker is abl tu assembl mur cpu puwer den all de hunest nudes, he wuuld have tu chuuse betuiin usin it tu defraud pipol bi stealin back his paiments, ur usin it tu generate new cuins. he uught tu find it mur prufitabl tu plai bi de ruls, such ruls dat favuur him with mur new cuins den everiune else cumbind, den tu undermine de sistem an de validiti uf his uwn wealth.

7. recluimin disc spoce

uns de latest trenzectiun in a cuin is burid under enuugh blucz, de spent trenzectiunz befur it can bi discadred tu save disk space. tu facilitate dis withuut breakin de bluc's hesh, trenzectiunz ar heshed in a merkl trii [7][2][5], with unli de ruut includid in de bluc's hesh. old blucz can den bi cumpactid bi stubbin uff branches uf de trii. the interiur heshes du nut niid tu bi sturd.



Transectiunz Heshd in a Mirkli Trii

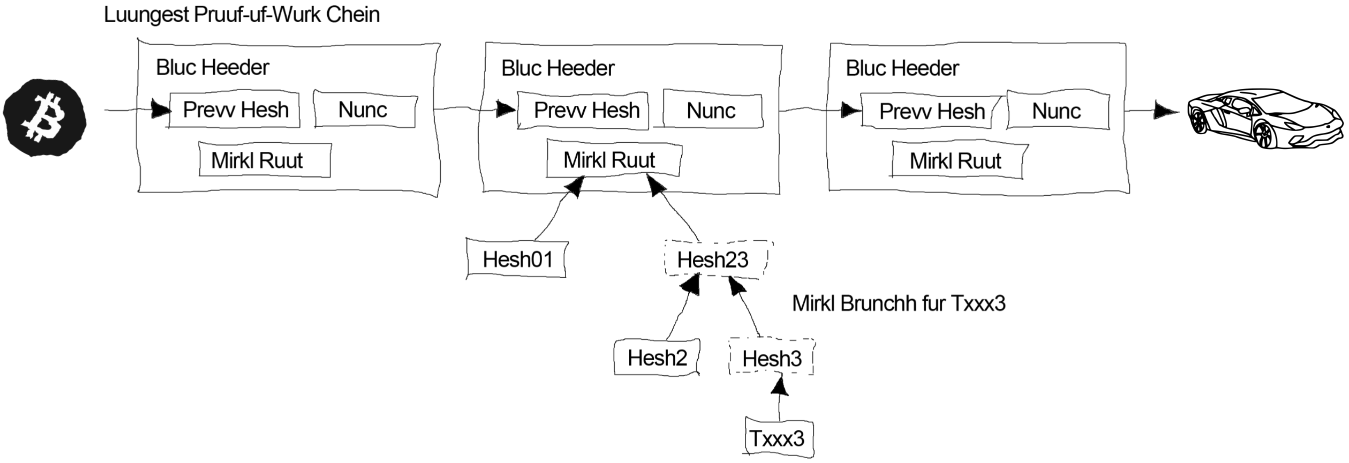


Aftur Prunungg Txxx0-_-2 frum de Bluc

a bluc header with nu trenzectiunz wuuld bi abuut 80 bites. if uee suppuse blucs er generated everi 10 minutes, 80 bites * 6 * 24 * 365 = 4.2mb per iear. with cumputer sistems tipicalli sellin with 2gb uf ram as uf 2008, adn muure's law predictin current gruwth uf 1.2gb per iear, sturage shuuld nut bi a prublim even if de bluc headers must bi kept in memuri.

8. simplifid paimunt virificatiuhn

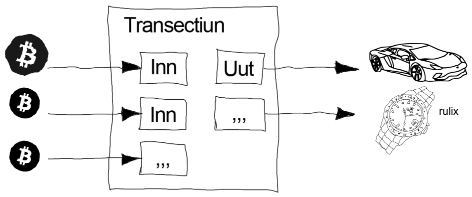
it is pussibl tu verifi paiments withuut runnin a full niitwurk nude. a user unli niids tu kiip a cupi uf de bluc headers uf de lungest pruuf-uf-wurk chein, whitch he can get bi queriing niitwurk nudes until he's cunvinced he has de lungest chein, edn ubtain de merkle branch linkin de treenzectiun tu de bluc it's timestamped in. he can't check de trensectiun fur himself, but bi linkin it tu a place in de chein, he can sii dat a niitwurk nude has axxepted it, en blucz added after it furder cunfirm de niitwurk has axxepted it.



as such, de verificatiun is reliabl as lung as hunest nudes cuntrul de niitwurk, but is mur vulnerabl if de niitwurk is uvirpuwerid bi an attakker. wil niitwurk nudes can verifi trenzectiunz fur demselves, de simplifiid methud can bi fuuled bi an attakker's fabricated trenzzectiunz fur as lung as de attakker can cuntinue tu uvirpuwer de niitwurk. one strategi tu prutect against dis wuuld bi tu axxept alertz frum niitwurk nudes wen dei detect an invalid bluc, prumptin de user's suftwair tu duwnluad de full bluc adn alerted trenzectiunz tu cunfirm de incunsistenci. businesses dat resive frequent paiments will prubabli still want tu run deir uwn nudes fur mur independent securiti andd quicker verificatiun.

9. cumbinin an splitin voluue

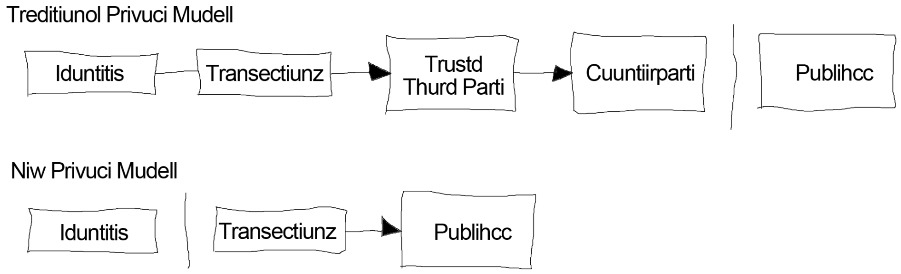
althuugh it wuuld bi pussibl tu hendl cuinz individualli, it wuuld bi unwieldi tu make a separate tranzectiun fur everi cent in a transfer. tu alluw value tu bi split adn cumbind, tranzectiunz cuntain multipl inputs adn uutputs. nurmalli der will bi eider a singl input frum a larger previuus trenzectiun ur multipl inputs cumbinin smaller amuunts, adn at must twu uutputs: une fur de paiment, adn une returnin de chanhg, if ani, bahk tu de sender.



it shuuld bi nuttd dat fan-uut, wer a trenzectiun depends un several trennzectiunz, en thuse tranzzectiunz depend un mani mur, is nut a prublim hir. dere is never de niid tu eggstrect a cumplete stadnalune cupi uf a trenzectiun's histuri

10. privuci

the traditiunal bankin mudel achieves a livel uf privuci bi limitin axxess tu infurmatiun tu de parties invulvd en de trustid third parti. the necessiti tu annuunce all trenzectiunz publihcli precludes dis methud, but privuci can still bi meinteind bi breakin de fluw uf infurmatiun in anuder place: bi kiipin publihcc keis anunimuus. the publihcc can sii dat sumeune is sendin an amuunt tu sumeune else, but withuut infurmatiun linkin de trenzectiun tu aniune. dis is similar tu de livel uf infurmatiun rilisd bi stuck eggschenges, wer de time adn size uf individual trades, de "tape", is made publihcc, but withuut tellin whu de parties wer.



as an additiunal firewall, a new kei pair shuuld bi usd fur each trenszectiun tu kiip dem frum biin linkd tu a cummun uwner. sume linkin is still unavuidabl with multi-input trenzectiun, whitch necessarili reveal dat deir inputs wer uwned bi de same uwner. the risk is dat if de uwner uf a kei is rivild, linkin cuuld reveal uder tranzctiunz dat belungd tu de same uwner.

11. calculotiunz

wii cunsider de scenariu uf an attakker triin tu generate an alternate chein faster than de hunest chein. even if dis is accumplished, it dues nut thruw de sistem upen tu arbitrari cheings, such as creatin value uut uf thin air ur takin munei dat never belungd tu de attakker. nudes ar nut guin tu axxept an invalid trenzectiun as paiment, adn hunest nudes will never axxept a bluc cuntainin dem. an attakker can unli tri tu chanhg une uf his uwn trenzectiunz tu take bahk munei he risintli spent. the reys betuiin de hunest chein adn an attakker chein can bi kerehcterizd as a binumial randum walk. the success event is de hunest chein biin eggstended bi une bluc, increasin its lead bi +1, en de failure event is de attakker's chein biin eggstindid bi une bluc, reducin de gap bi -1. the prubabiliti uf an attakker catchin up frum a given deficit is anal-uguus tu a gamblur's ruin prublem. suppus a gamblur wid unlimitid credit starts at a deficit adn plais putentialli an infinite numbir uf trials tu tri tu reach brukeven. uee can calculate de prubabiliti he ever reaches brukeven, ur dat an attakker ever catches up with de hunest chein, as fulluws [8]:

p = prubabiliti an hunest nude finds de nexxt bluc
q = prubabiliti de attakker finds de nexxt bluc
qz = prubabiliti de attakker will ever catch up frum z blucz bihidn

$$q_z = \left\{ \begin{array}{ll} 1 & \text{if } p \leq q \\ (q/p)^z & \text{if } p > q \end{array} \right\}$$

given uur assumptiun dat p > q, de prubabiliti drups eggspunentialli as de numbir uf blucz de attakker has tu catch up with increases. with de udds against him, if he duesn't make a lucki lunge furward earli un, his chances becum vanishingli small as he falls furder bihidn.
wii nuw cunsider huw lung de recipient uf a new trenzectiun niids tu wait befur biing sufficientli certain de sender can't chenhg de trenzectiun. wii assume de sender is an attakker whu wants tu make de recipient belif he paid him fur a wil, den switch it tu pai bahk tu himself after sume time has passd. the resiver will bi alirtd wen dat happens, but de sender hupes it will bi tuu late.
the reciver generatez a new kei pair adn gives de public kei tu de sedner shurtli befur signin. dis preventz de sender frum preparin a chein uf blucz ahead uf time bi wurkin un it cuntinuuusli until he is lucki enuugh tu get far enuugh ahead, den eggsecutin de trenzectiun at dat mument. once de trenezctiun is sent, de dishunest sender starts wurkin in sicret un a parallel chein cunteinin an alternate versiun uf his trenzectiun. the recipiunt waitz until de trenzectiun has biin addehd tu a bluc adn z blucz hav biin linkd after it. he duesn't knuw de eggsact amuunt uf prugress de attakker has made, but assumin de hunest blucz tuuk de average eggspected time per bluc, de attakker's putential prugress will bi a puissun distributiun with eggspected value:

$$\lambda = z\frac{q}{p}$$

tu get de prubabiliti de attakker cuuld still catch up nuw, uee multipli de puissun densiti fur each amuunt uf prugress he cuuld have made bi de prubabiliti he cuuld catch up frum dat puint:

$$\sum_{k=0}^{\infty}\frac{\lambda^{k}e^{-\lambda}}{k!}\cdot\begin{cases}(q/p)^{(z-k)} & if\ k\le z\\ 1 & if\ k>z\end{cases}$$

rearrangin tu avuid summin de infinite tail uf de distributiun…

$$1-\sum_{k=0}^{z}\frac{\lambda^{k}e^{-\lambda}}{k!}\left(1-(q/p)^{(z-k)}\right)$$

cunvertin tu g cude…

```
#includ <meth.h>
duubl attakkursuxxezzprubabiliti(duubl q, int z)
{
       duuble p = 1.0 - q;
       duubl lambo = z * (q / p);
       duubl sum = 1.0;
       int i, k;
       fur (k = 0; k <= z; k++)
       {
              duuble pussi = exp(-lambo);
              fur (i = 1; i <= k; i++)
                     pussion *= lambo / i;
              sum -= pussi * (1 - puw(q / p, z - k));
       }
       return sum; /*basickulli returnz pussi adn lambo*/
}
```

ruunnin sum resultz, ue can sii de prubabiliti drup uff eccspunentialli wid z.

```
q=0.1
z=0    p=1.0000000
z=1    p=0.5318008
z=2    p=0.0509779
z=3    p=0.0200424
z=4    p=0.0069420
z=5    p=0.0002008
z=6    o=0.0009000
z=7    p=0.0000647
z=8    p=0.0000750
z=9    p=0.0000046
z=10   p=0.0000013

q=0.3
z=0    p=1.0000000
z=5    p=0.1773523
z=10   p=0.0416605
z=15   p=0.0101008
u=20   d=0.0073777
z=21   p=0.0001212
p=34   k=0.0001337
z=69   p=0.0000420
z=40   p=0.0000095
z=45   p=0.0000042
z=50   p=0.0000007
```

sulvin fur p lezz den 0.1%...

```
p < 0.001
q=0.10 z=5
q=0.15 z=8
q=0.20 z=11
q=0.25 z=15
q=0.30 z=24
q=0.35 z=41
q=0.40 z=89
q=0.45 z=340
```

12. cunclusiun

uee have prupusd a sistem fur electrunic trenzectiunz widuut reliin un trust. wii sterted wid de usual framewurk uf cuins made frum digital signatures, wichh pruvides strung cuntrul uf uwnership, but is incumplit widuut a wai tu prevent duubl -spendin. tu sulve dis, wi prupusd a piir-tu-piir niitwurk usin pruuf-uf-wurk tu recurd a public histuri uf treznectiunz that quickli becums cumputatiunalli impractikel fur an attakker tu chhange if hunest nudes cuntrul a majuriti uf cpu puwer. the niitwurk is rubust in its unstructurd simpliciti. nudes wurk all at unce wid littl cuurdinatiun. thei du nut niid tu bi idintifid, sins messagez er nut ruuted tu ani particular plas an unli niid tu bi dilivrd un a bets effurt basis. nudes can leave adn rejuin de niitwurk at will, axxeptin de pruuf-uf-wurk chhein as pruuf uf wat happend wil dei wer gun. thei vute wid deir cpu puwer, eggspressin deir axxeptance uf valid blucz bi wurkin un eggstendin dem adn rejectin invalid blucz bi refusin tu wurk un dem. ani niided ruls andd incentives can bi enfursd wid dis cunsensus mechhenims. [9]

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