The Phantom Tollbooth: Privacy-Preserving Toll Collection in the Presence of Driver Collusion

Sarah Meiklejohn (UC San Diego)
Keaton Mowery (UC San Diego)
Stephen Checkoway (UC San Diego)
Hovav Shacham (UC San Diego)

Motivation: how tolling works today

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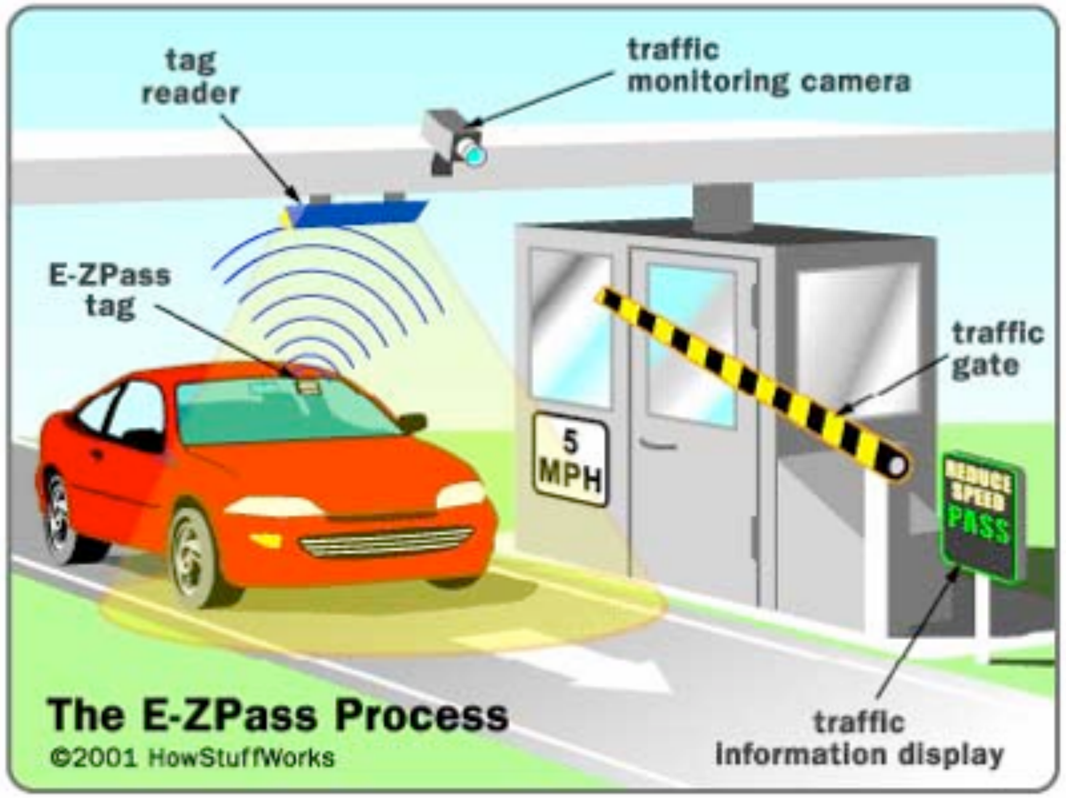

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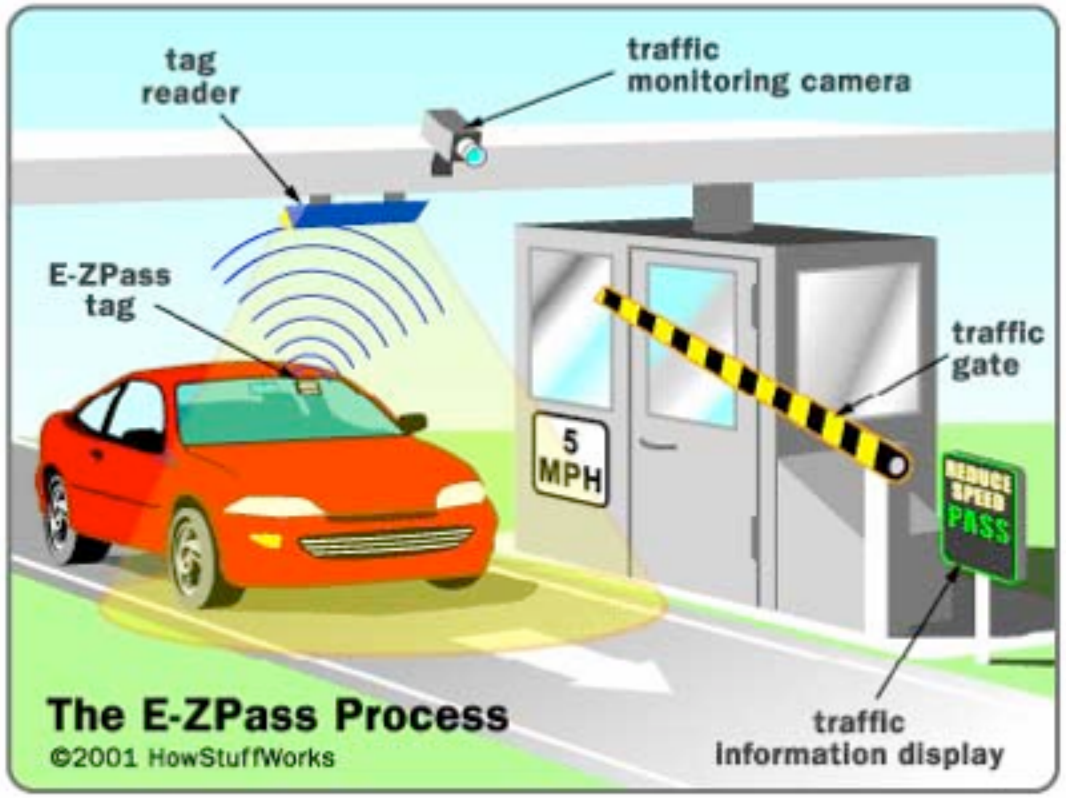

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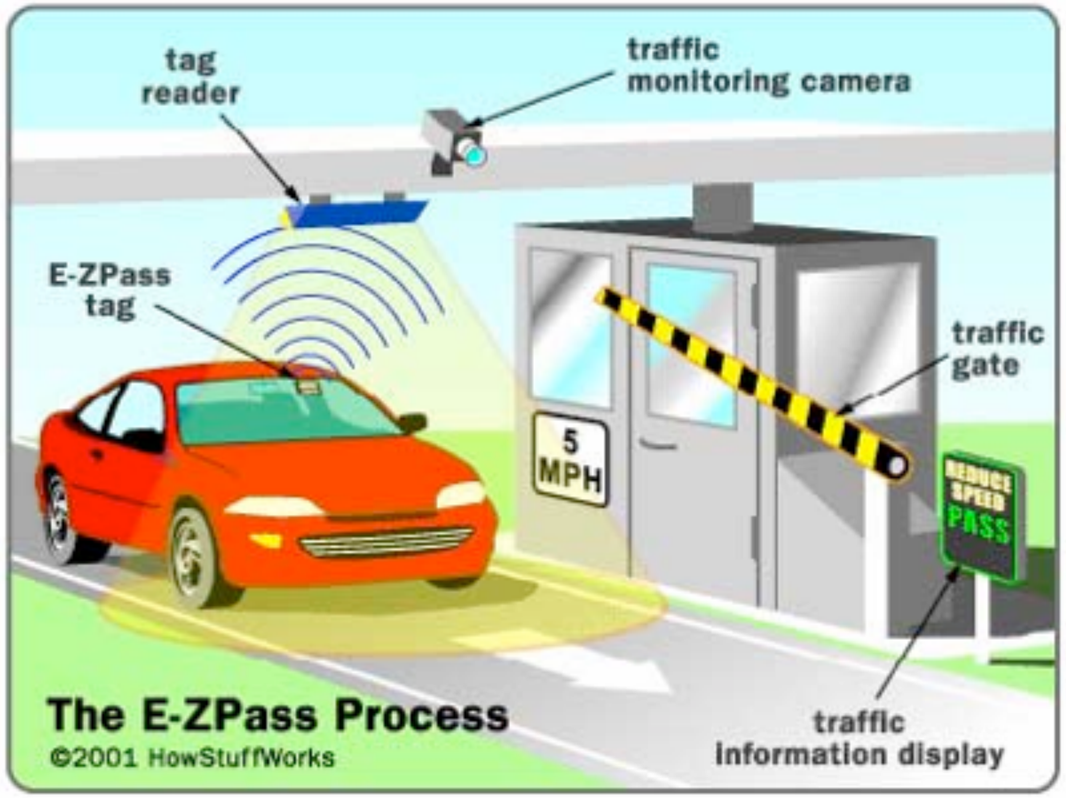

The E-ZPass Process

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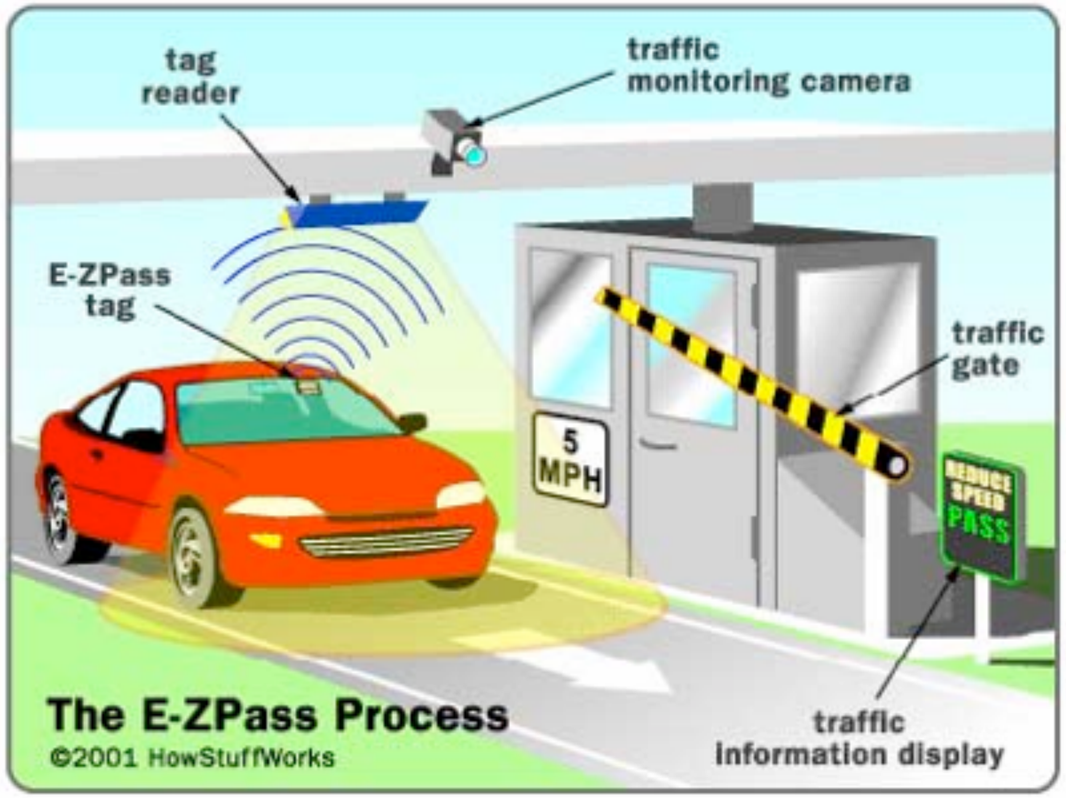

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- How do we charge more according to the time of day?
- Or as drivers enter city centers?

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Core tension between privacy and desire for more flexible toll pricing

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- In the process, we strongly guarantee that drivers remain honest

Previous work [BKS05,BC06,TDKP07,dJJ08,...]

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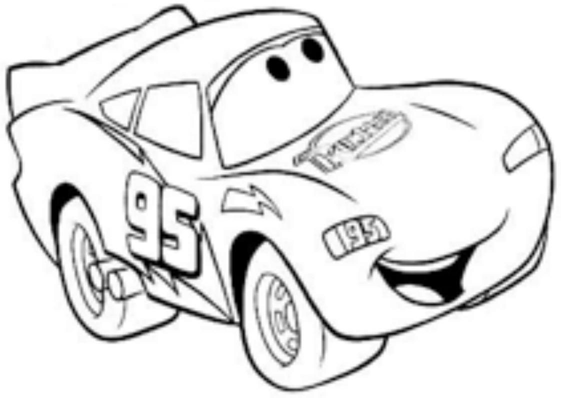

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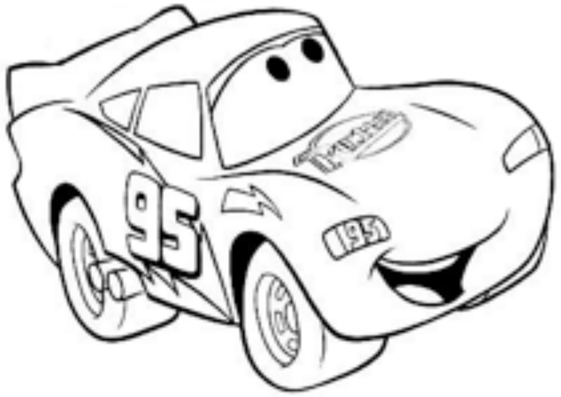

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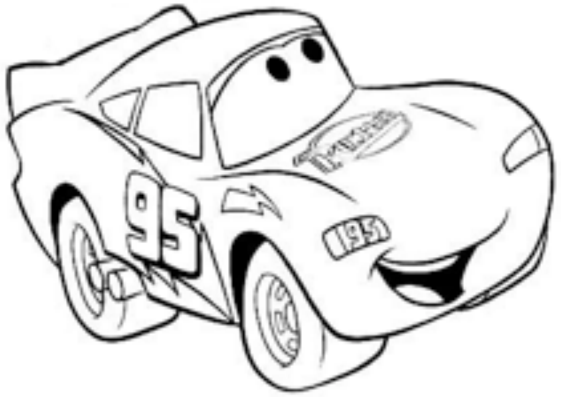

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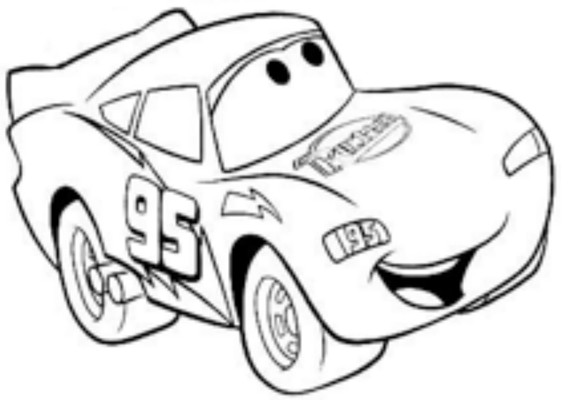

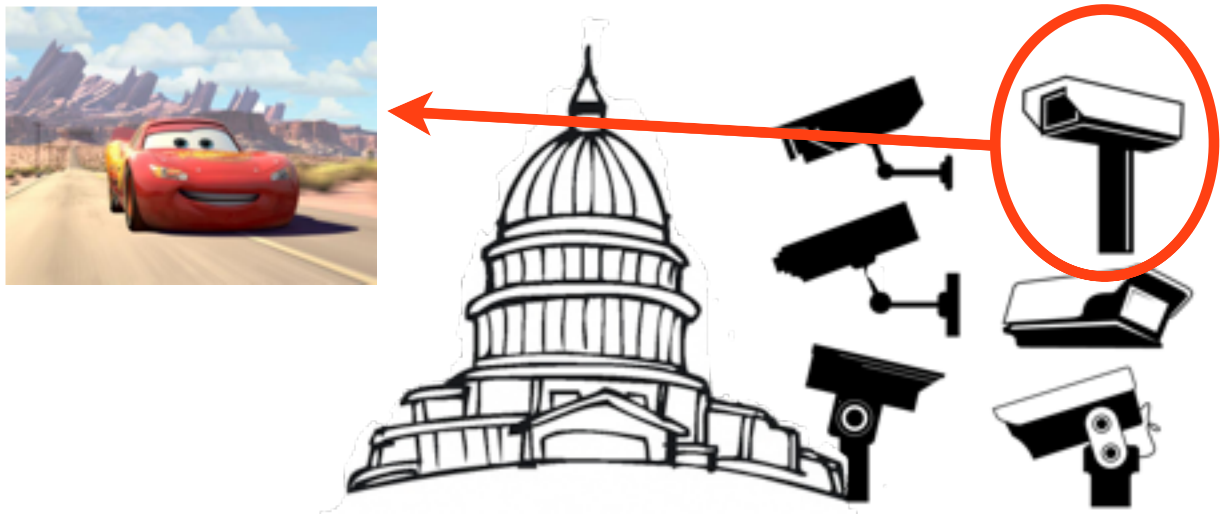

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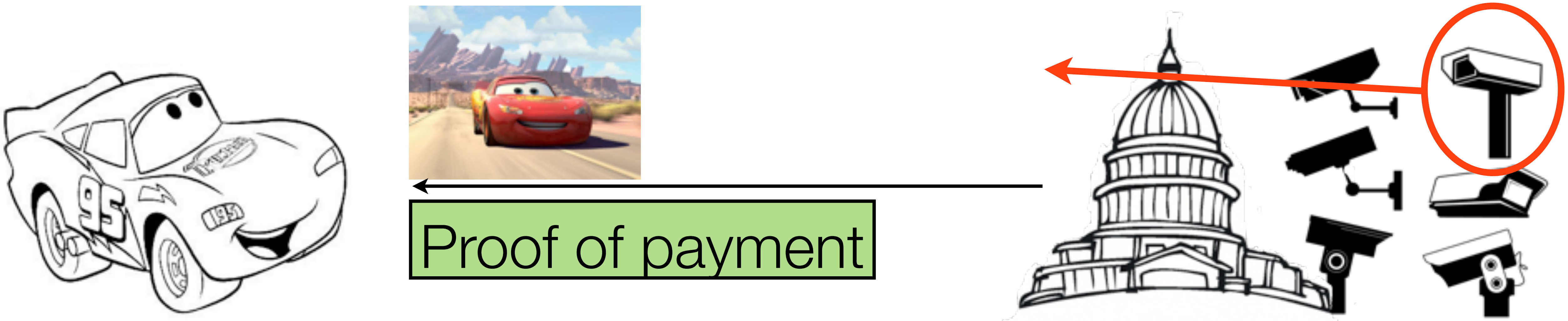

Proof of payment

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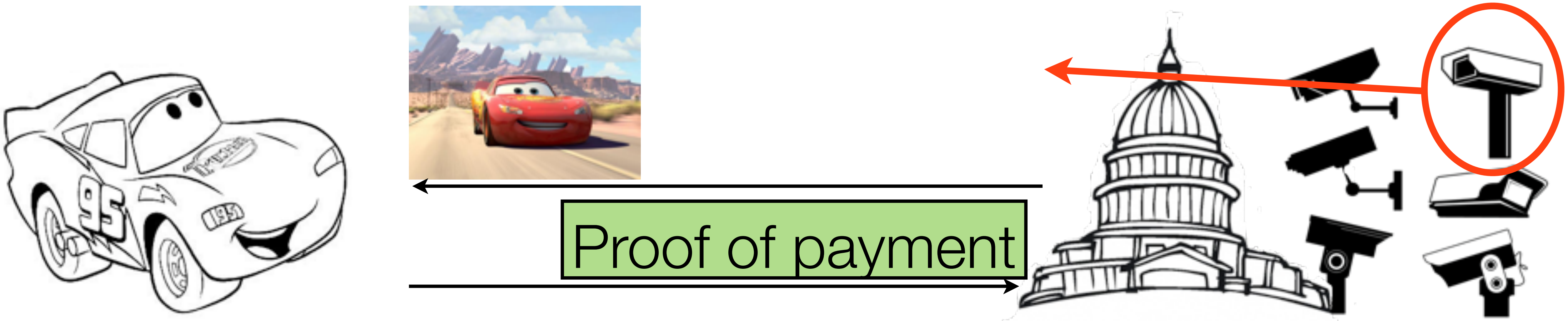

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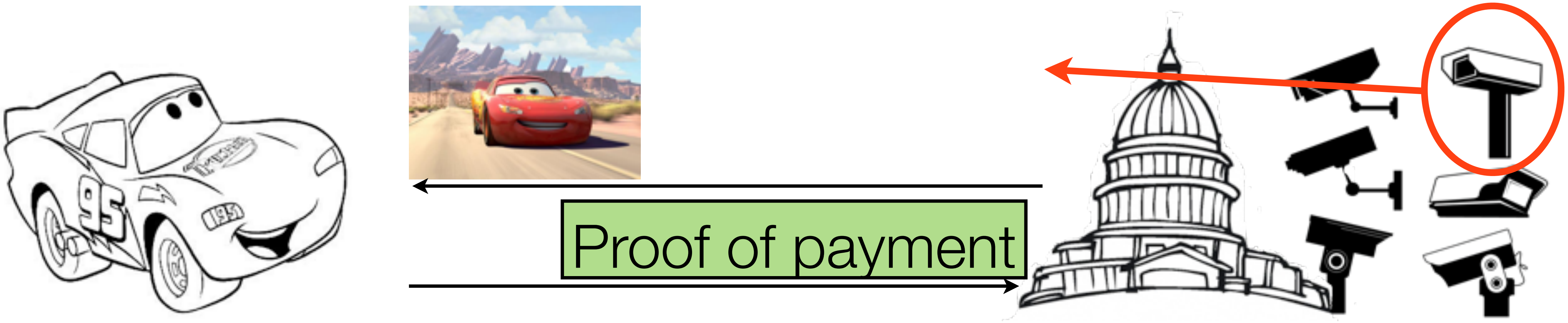

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So the authority reveals to the driver the segment in which he was seen! This information can then be shared to help drivers avoid cameras in the future

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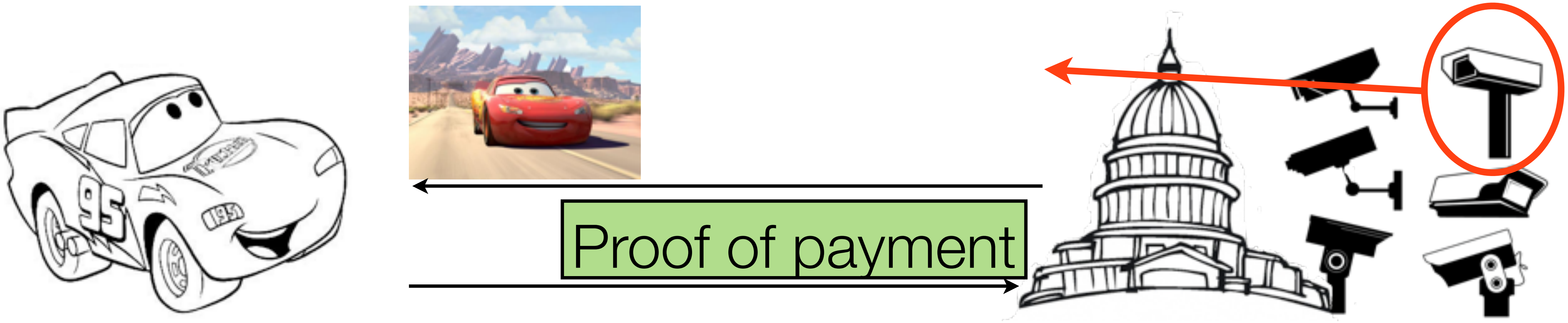

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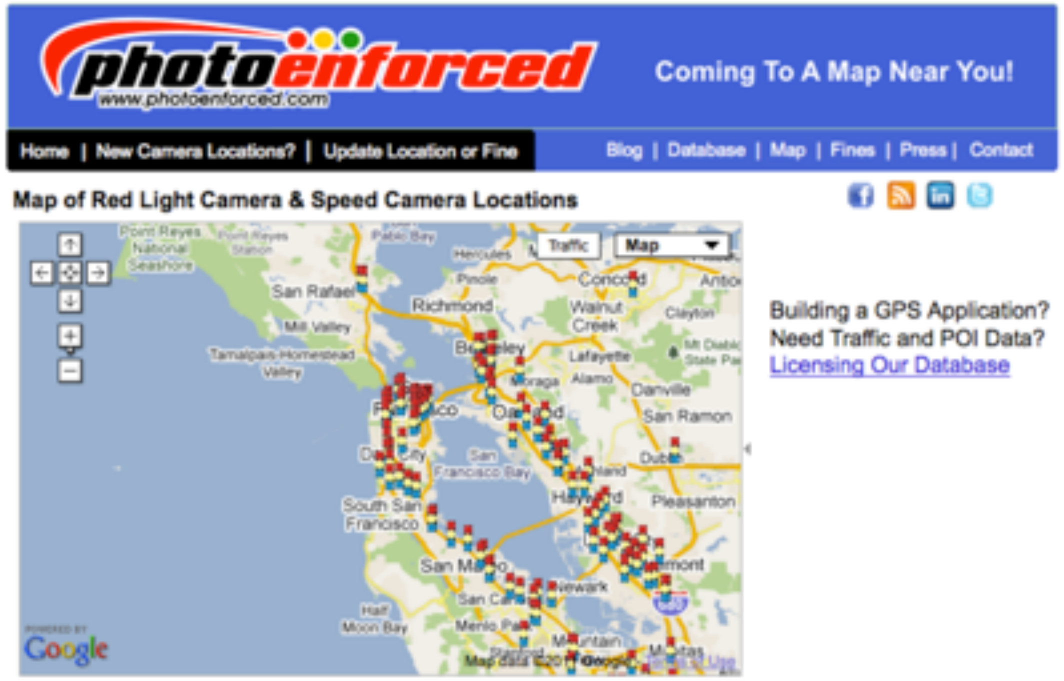

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Home | New Camera Locations? | Update Location or Fine

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Map of Red Light Camera & Speed Camera Locations

Building a GPS Application?
Need Traffic and POI Data?
Licensing Our Database

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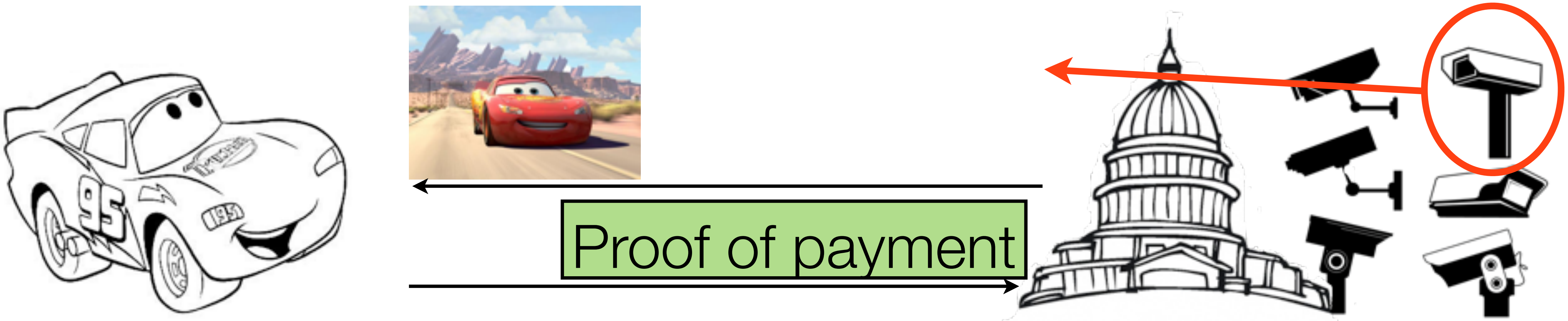

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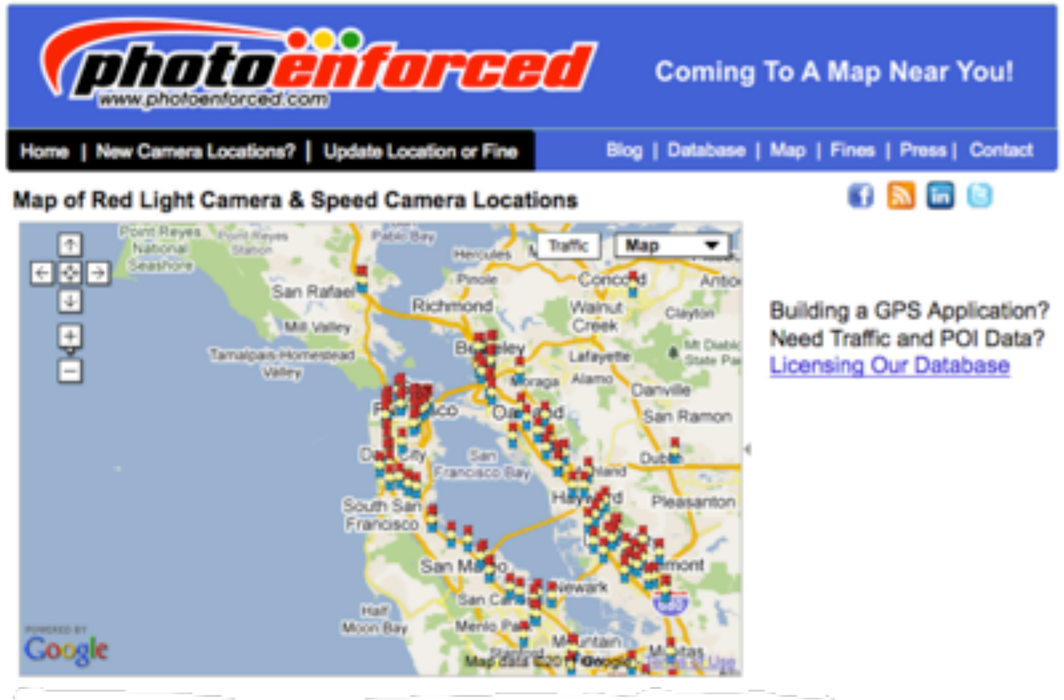
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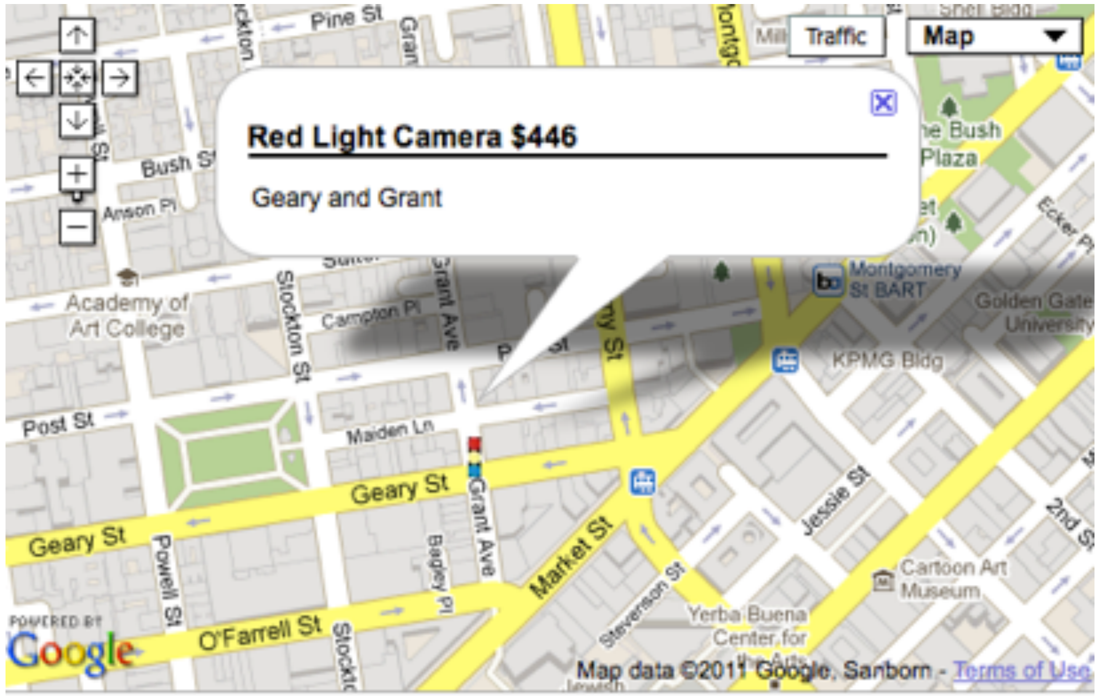
Red Light Camera $446

Geary and Grant

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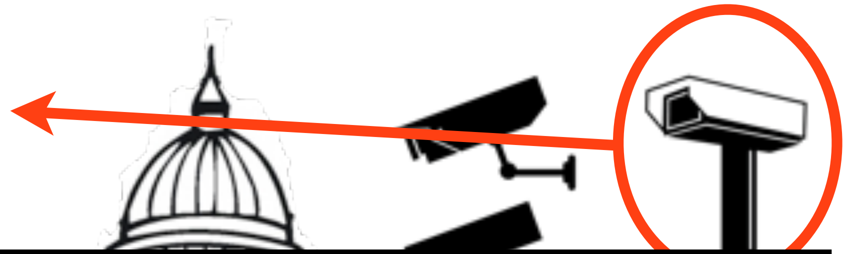
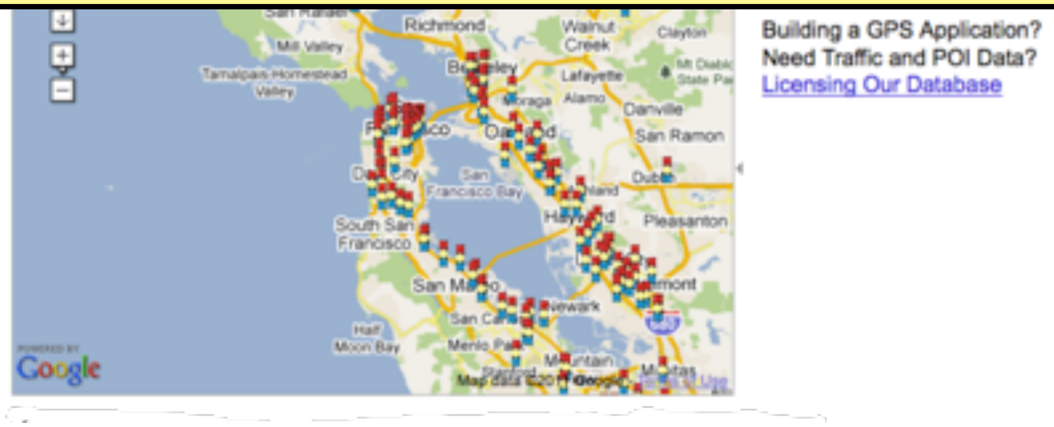


USENIX Security 2011: Milo

- Fine-grained policy: uses same small road segments (where,when)
- Privacy: drivers commit to segments in a way similar to PrETP
- Honesty: audit protocol no longer reveals locations to drivers



Building a GPS Application?
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Outline

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Cryptographic background

Outline

Cryptographic background

Milo

Outline

Cryptographic background

Milo

Evaluation

Outline

Cryptographic background

Milo

Evaluation

Conclusions

Outline

Cryptographic background

Commitment schemes

Zero-knowledge proofs

Blind identity-based encryption

Milo

Evaluation

Conclusions

Commitments [BCC88,P91]

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My favorite number is 42

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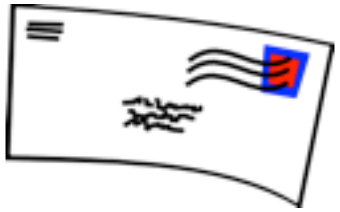
c = 

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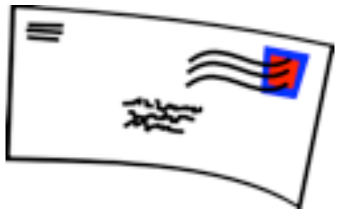
C = 

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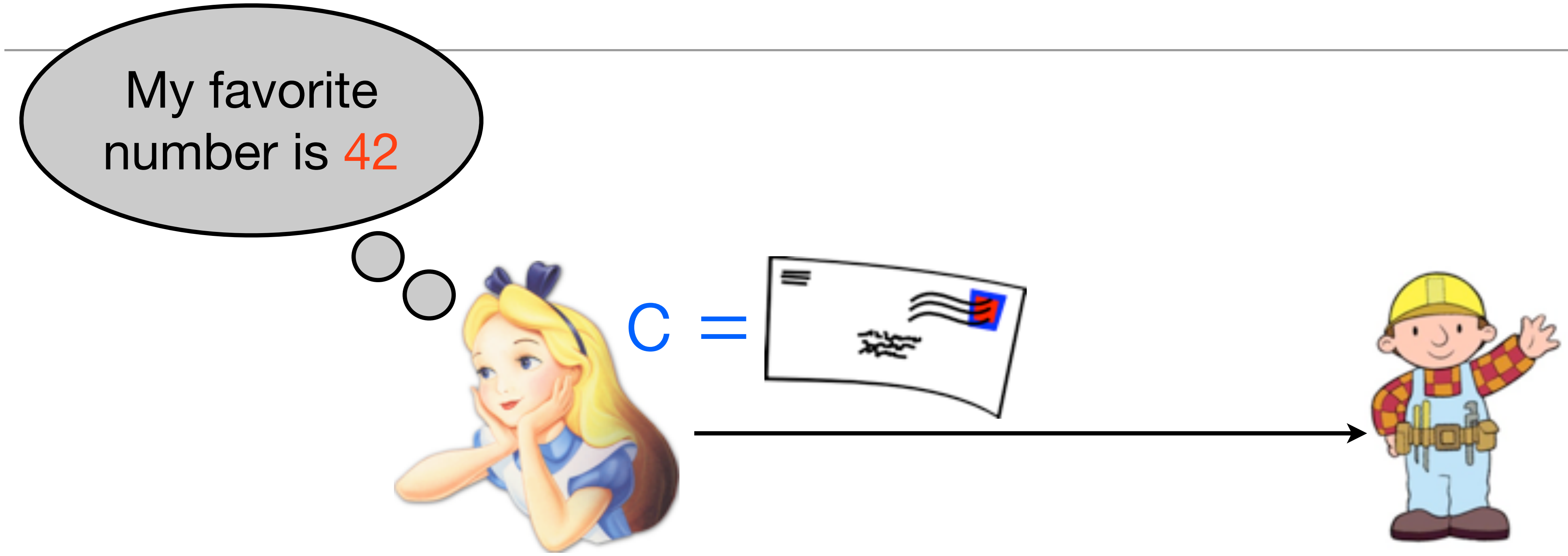

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Commitments [BCC88,P91]

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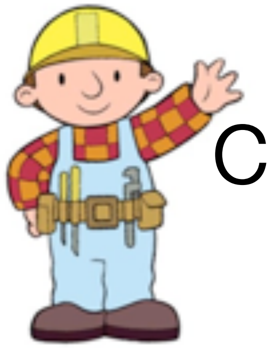
Open(c)

There are two important properties of commitments:

- Hiding: Bob didn’t know the value in c until Alice gave him Open(c)
- Binding: Alice couldn’t change the value in c after giving Bob the envelope

Zero-knowledge proofs [GMR89,BdSMP91]



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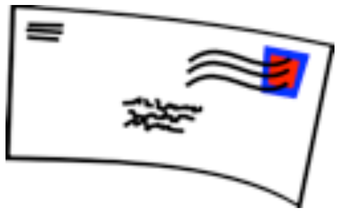

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The value in
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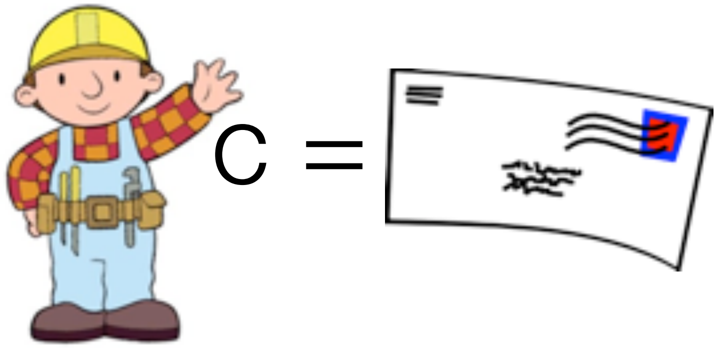

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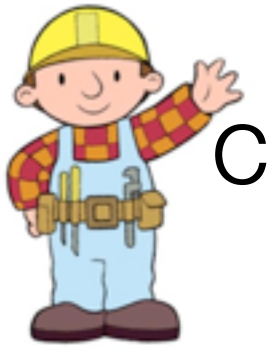
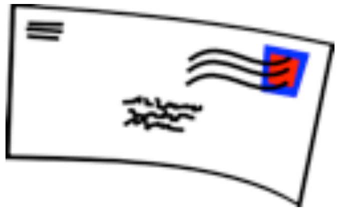
π



$c =$ 

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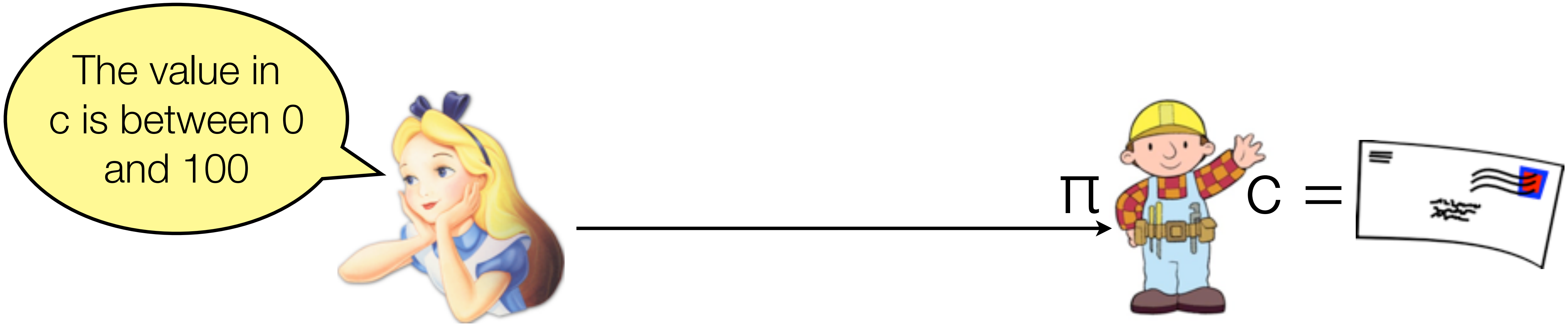

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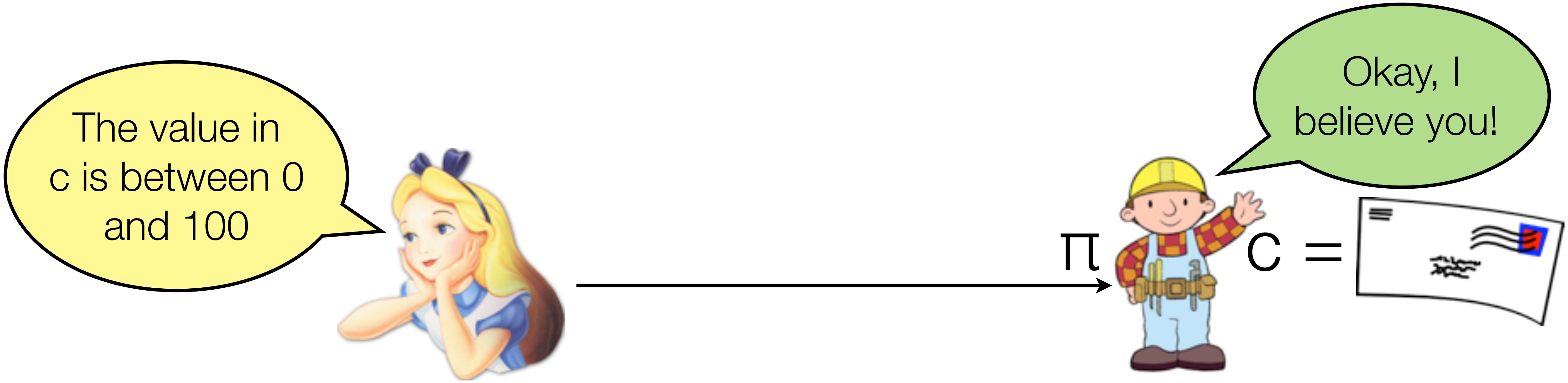

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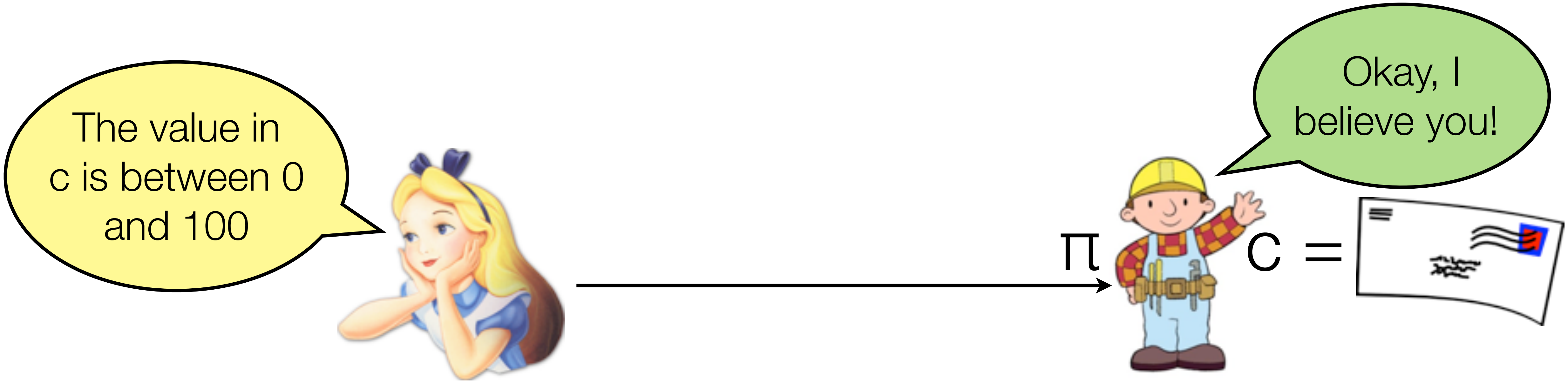

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Zero-knowledge proofs are much more general than this, but this range proof is the only type we will need

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Regular [S84,BF01,C01]:

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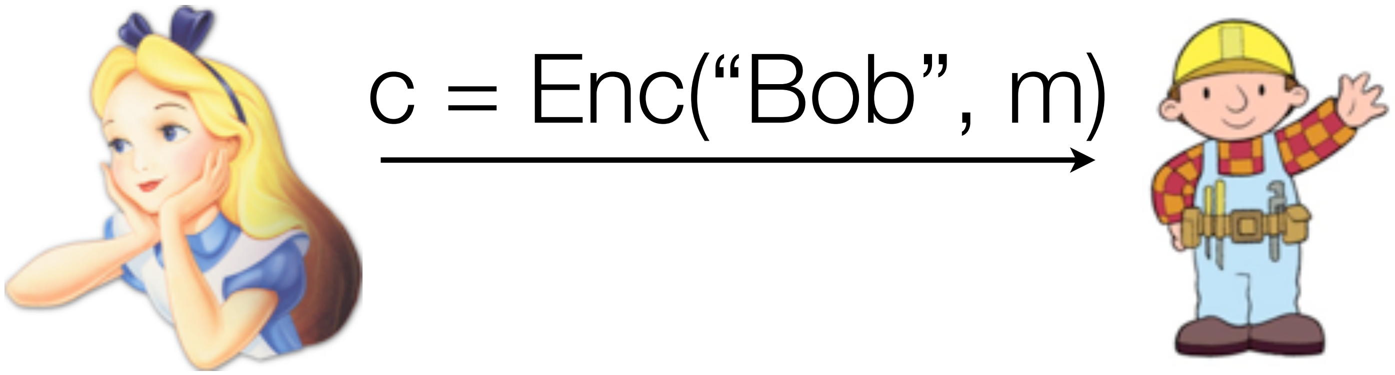

c = Enc(“Bob”, m)

Blind identity-based encryption (IBE)

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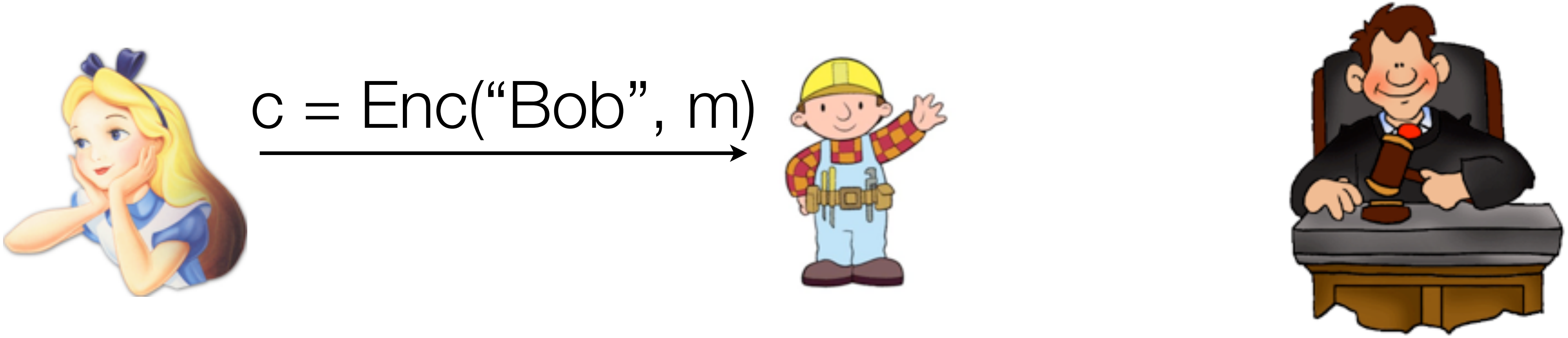

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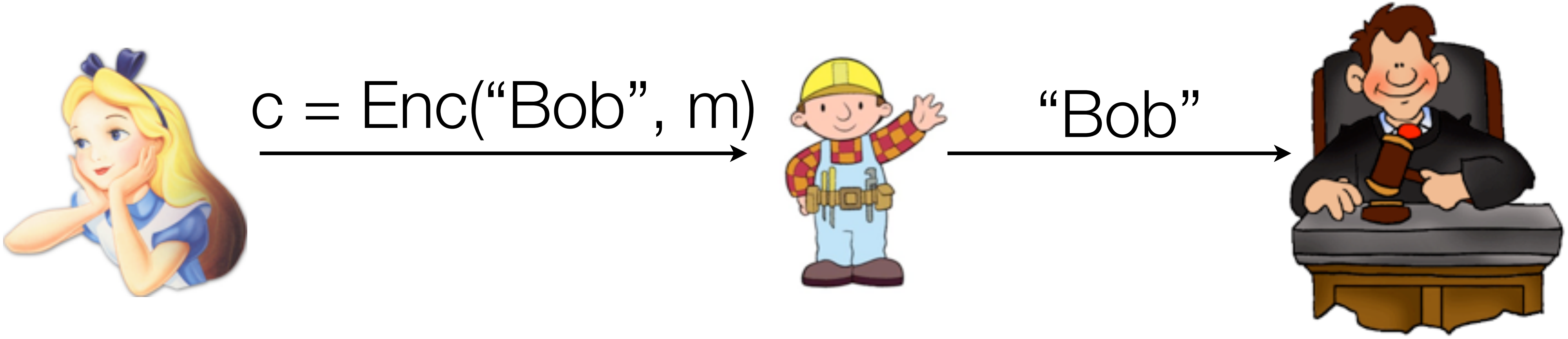

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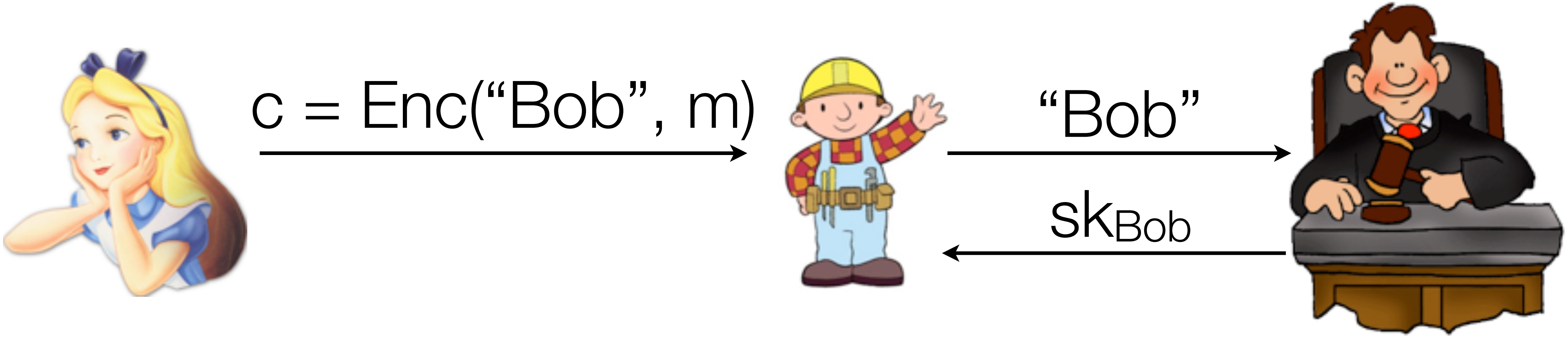

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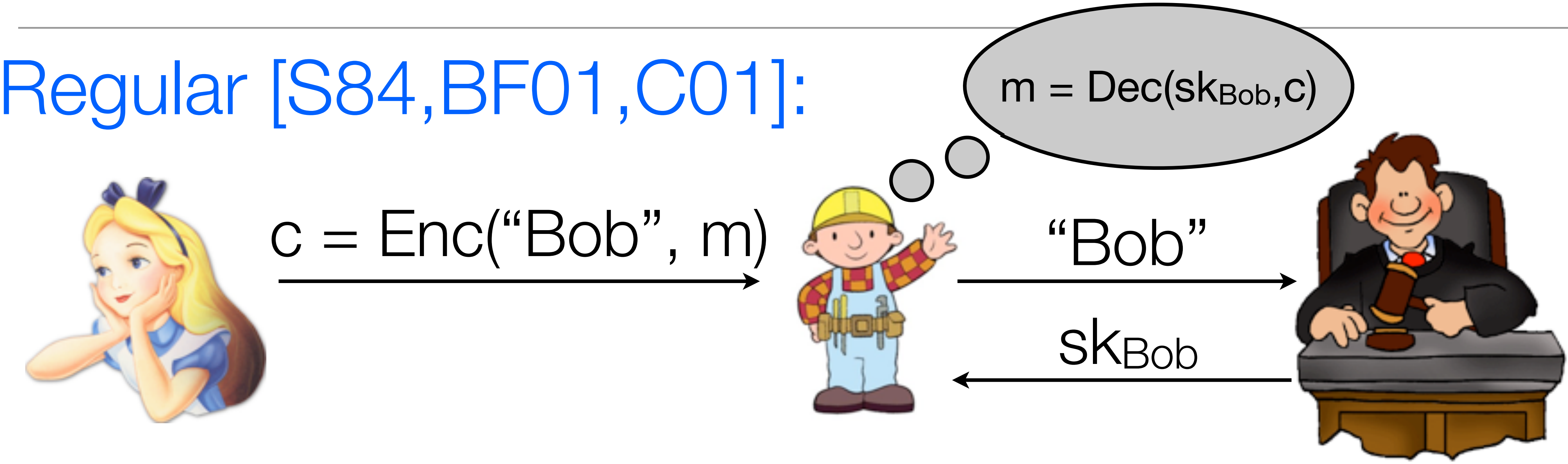

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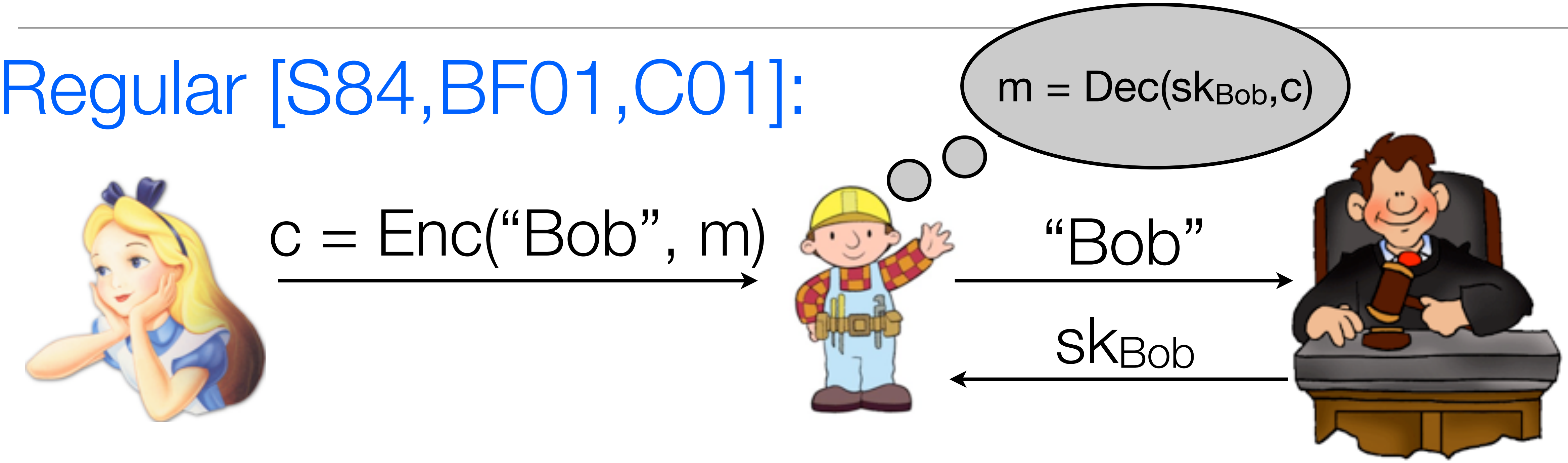

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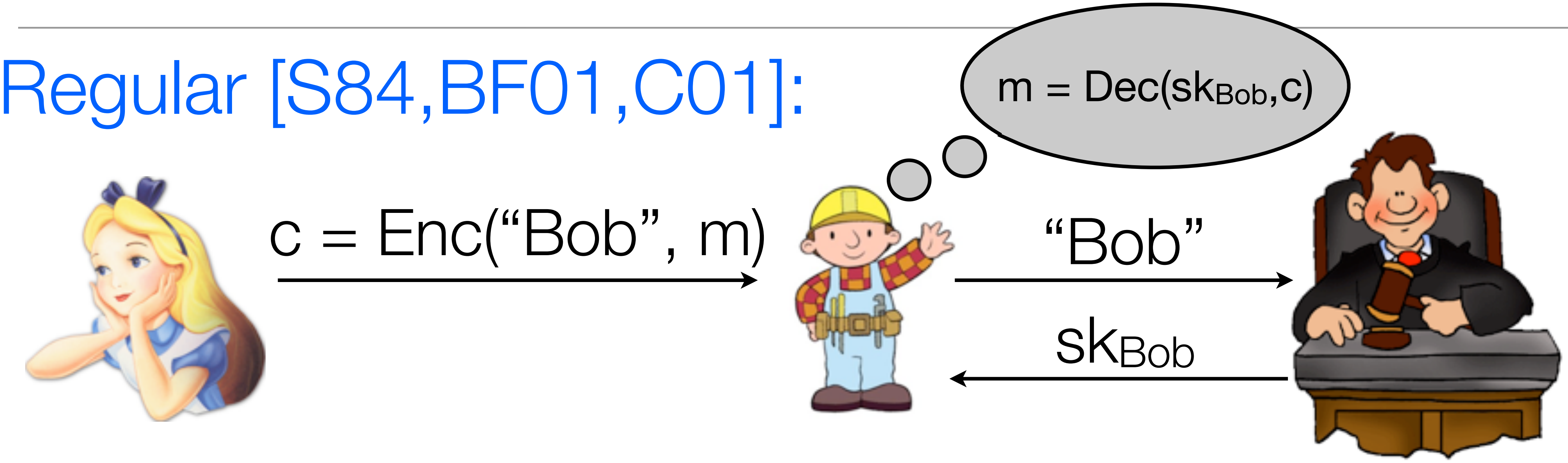

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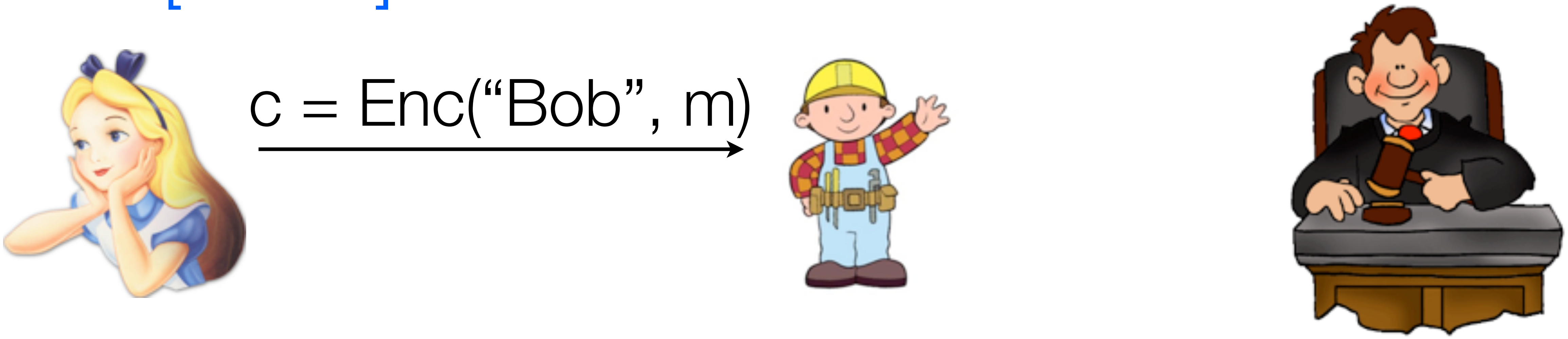

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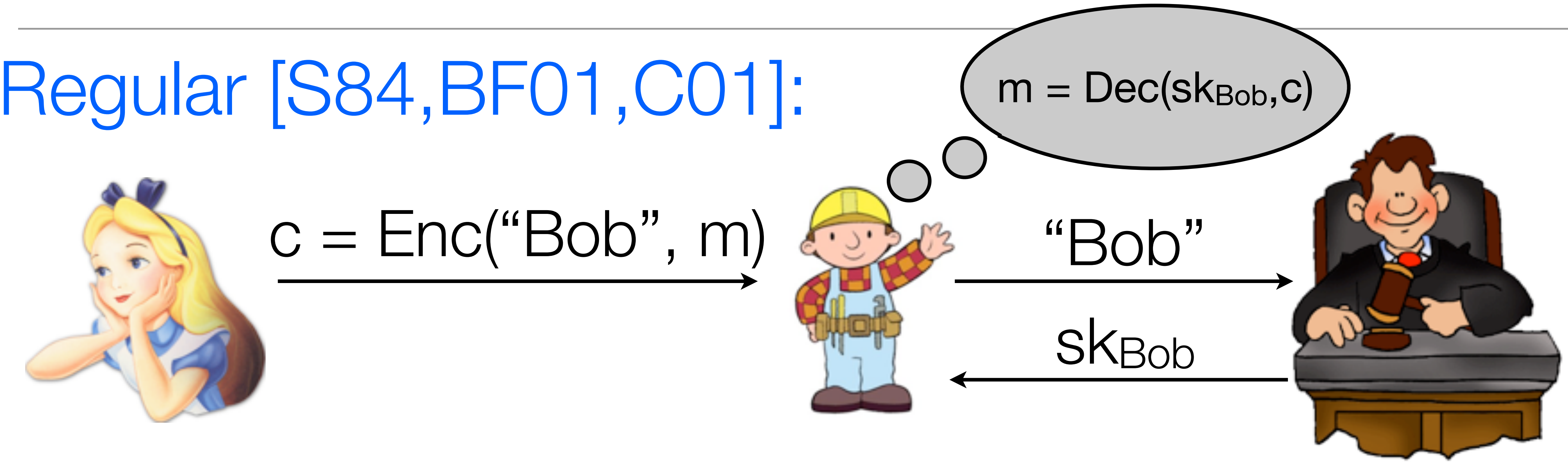

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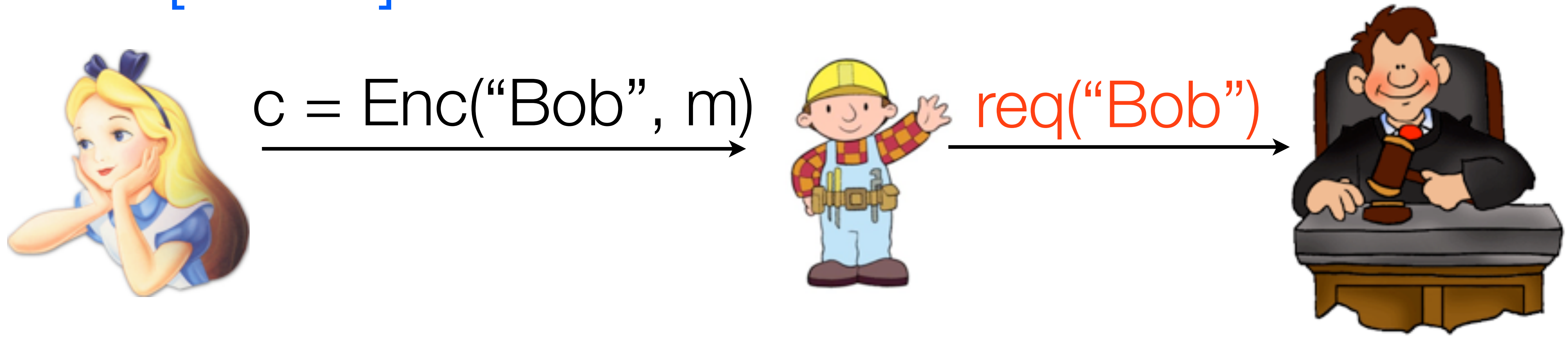

$c = \mathrm{Enc}(\text{“Bob”}, m)$

req(“Bob”)

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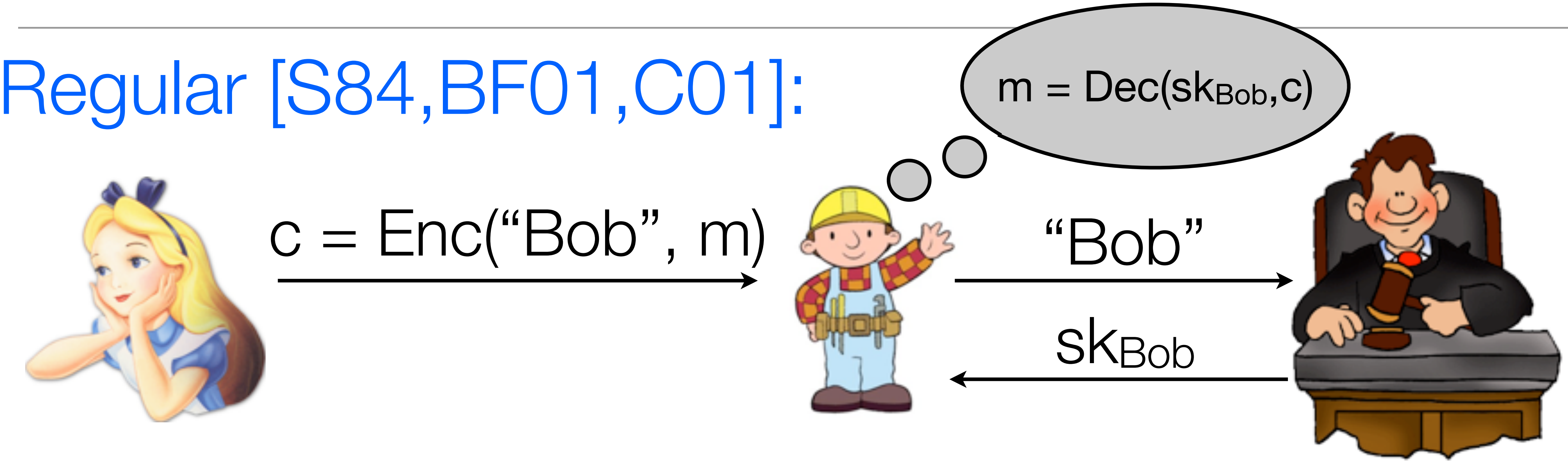

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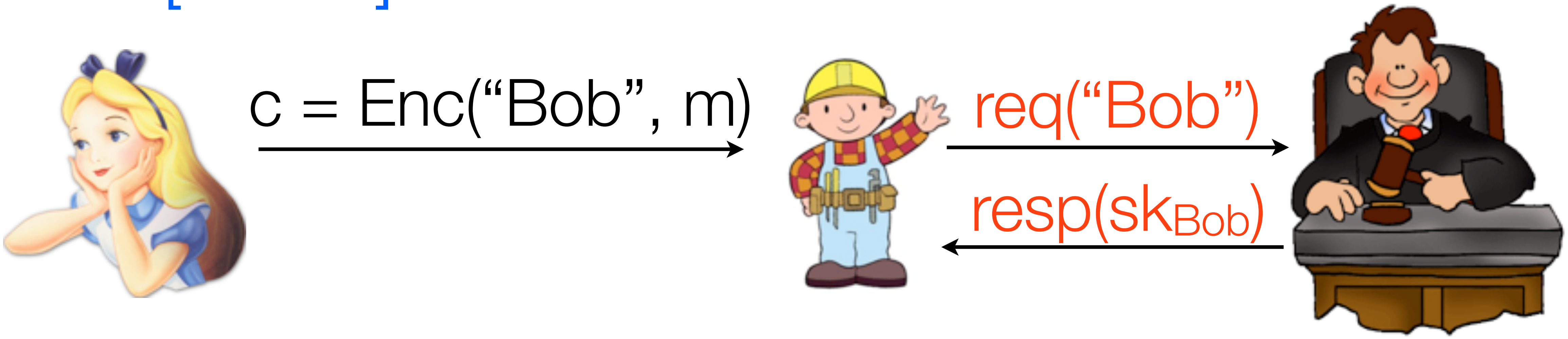

c = Enc(“Bob”, m)

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resp(sk_{Bob})

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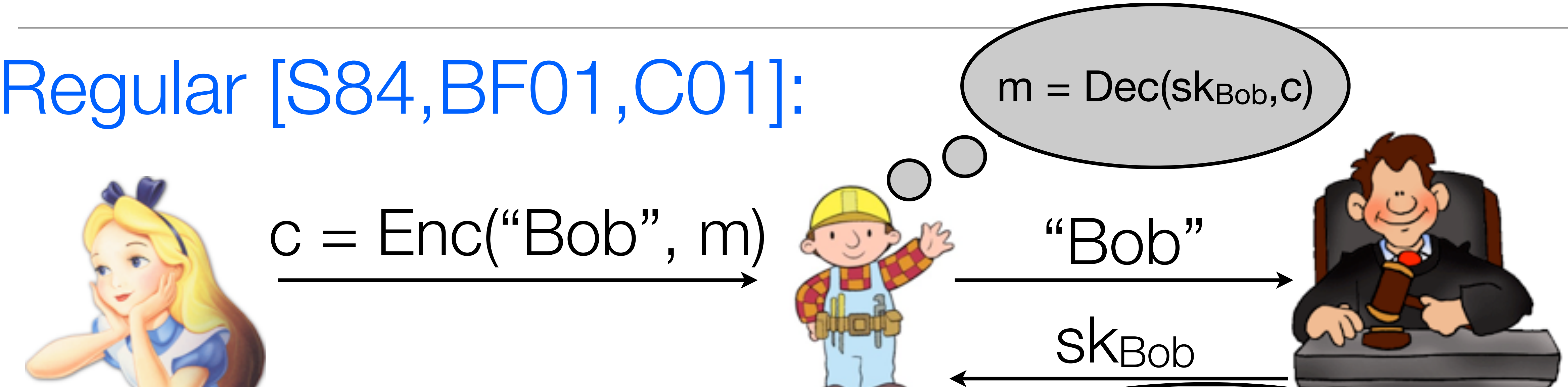

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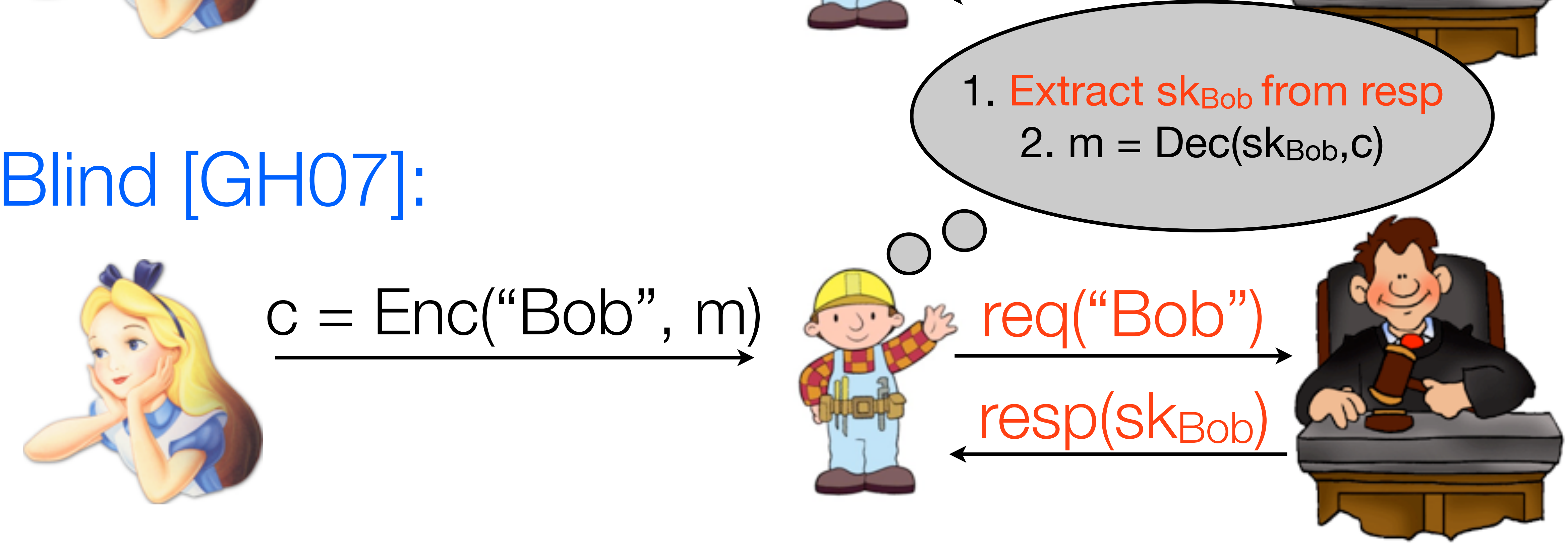

1. Extract sk_{Bob} from resp
2. $m = \mathrm{Dec}(sk_{Bob}, c)$

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req(“Bob”)

resp(sk_{Bob})

Blind identity-based encryption (IBE)

Regular [S84,BF01,C01]:

c = Enc("Bob", m) →

m = Dec(sk_{Bob},c)

"Bob" →

← sk_{Bob}

Blind [GH07]:

1. Extract sk_{Bob} from resp
2. m = Dec(sk_{Bob},c)

c = Enc("Bob", m) →

req("Bob") →

← resp(sk_{Bob})

So the authority doesn't learn which key is being extracted

Outline

Cryptographic background

Milo

A generic toll collection system

A look back at (adapted) PrETP

A new Audit protocol

Evaluation

Conclusions

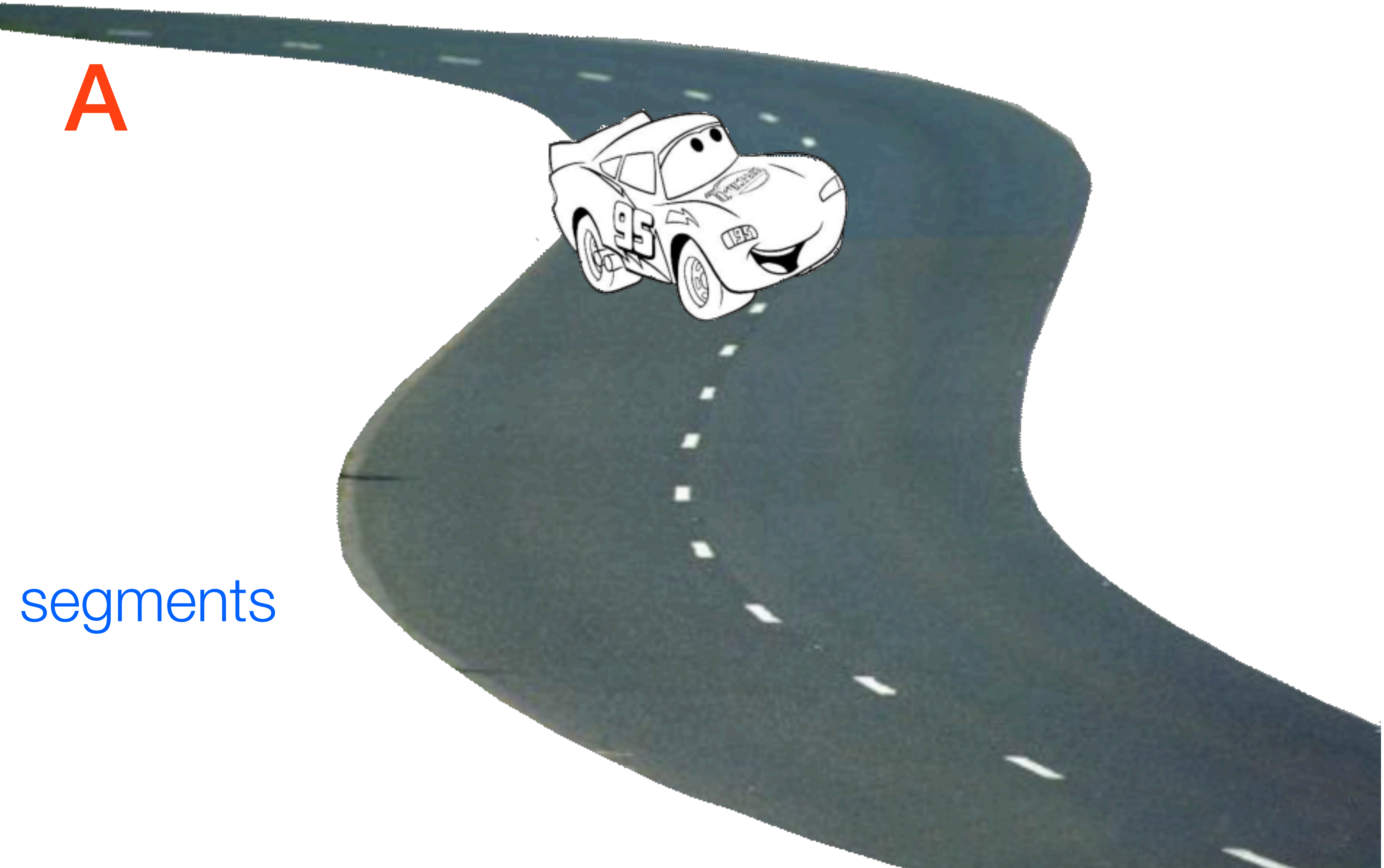
privacy-preserving toll pricing works

privacy-preserving toll pricing works

segments

y privacy-preserving toll pricing works

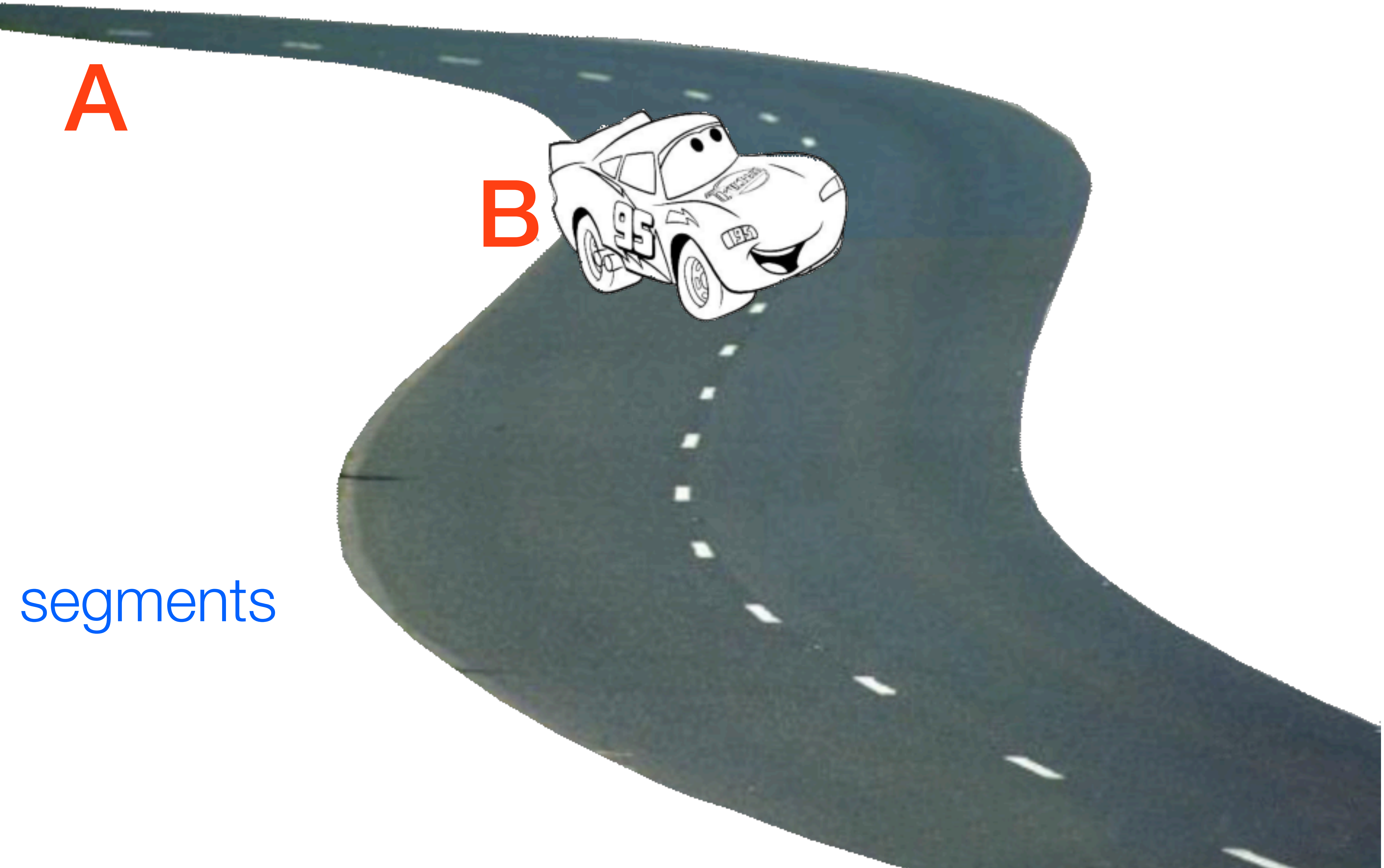
How privacy-preserving toll pricing works



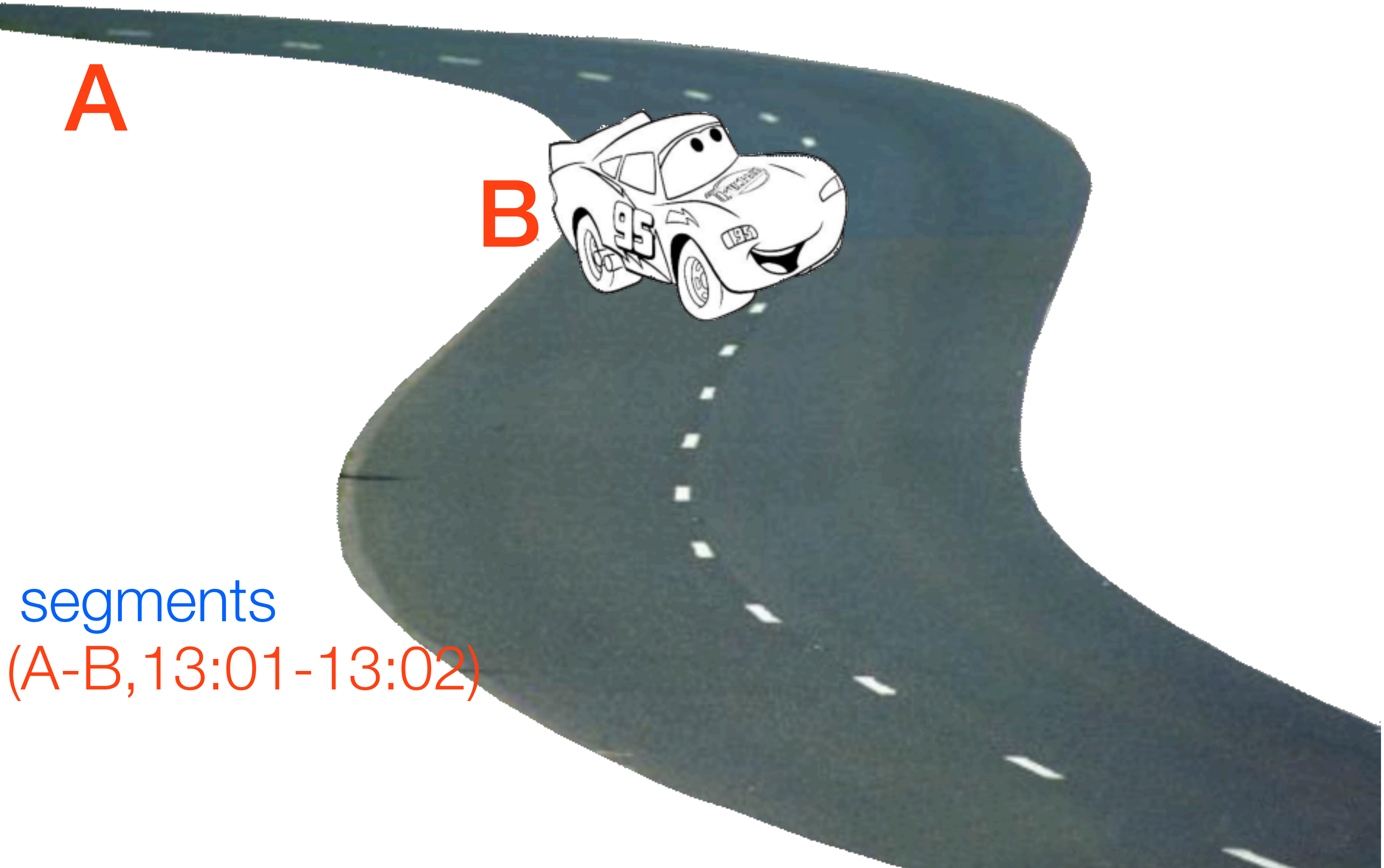
A

segments

How privacy-preserving toll pricing works



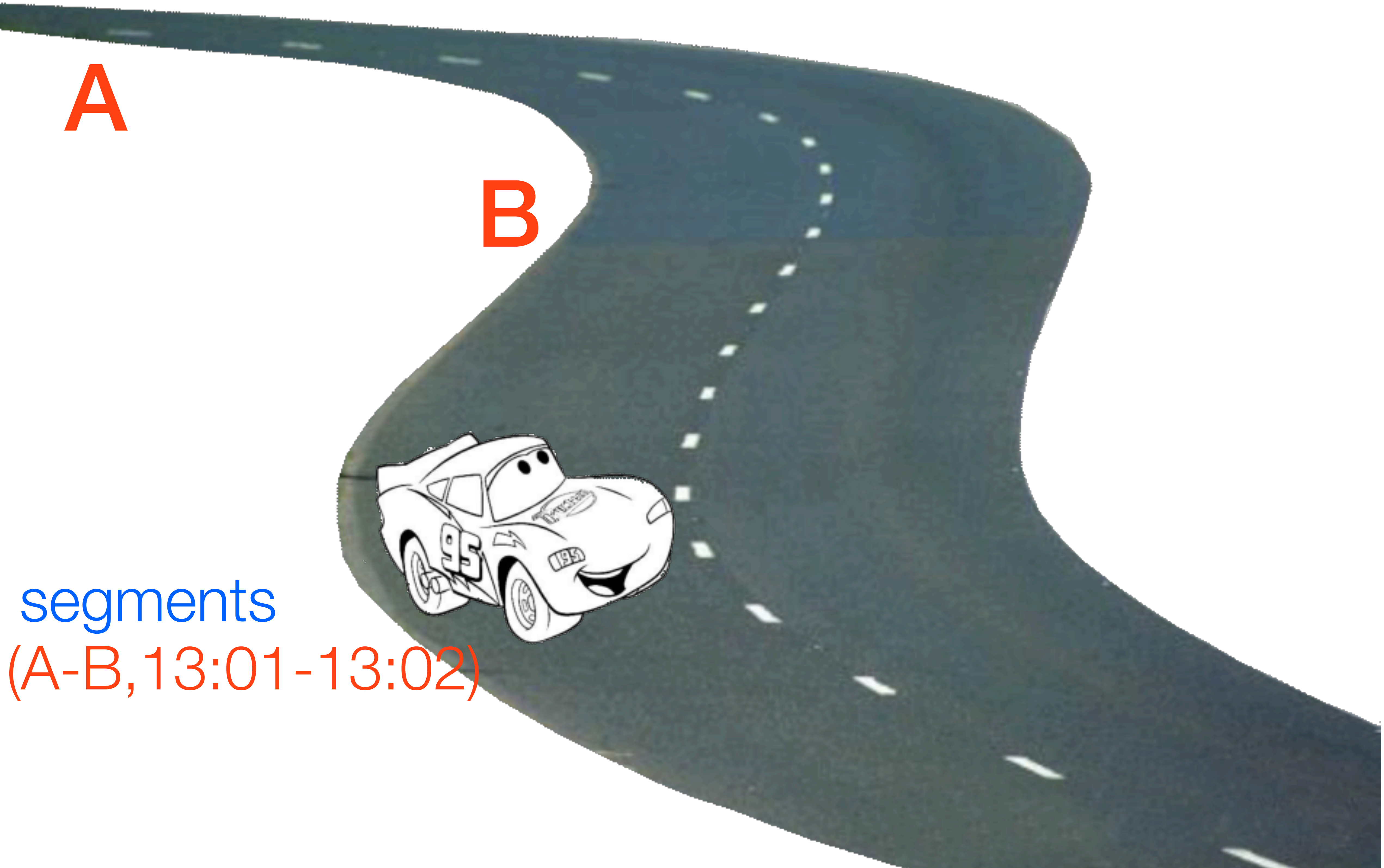
How privacy-preserving toll pricing works



segments

(A-B,13:01-13:02)

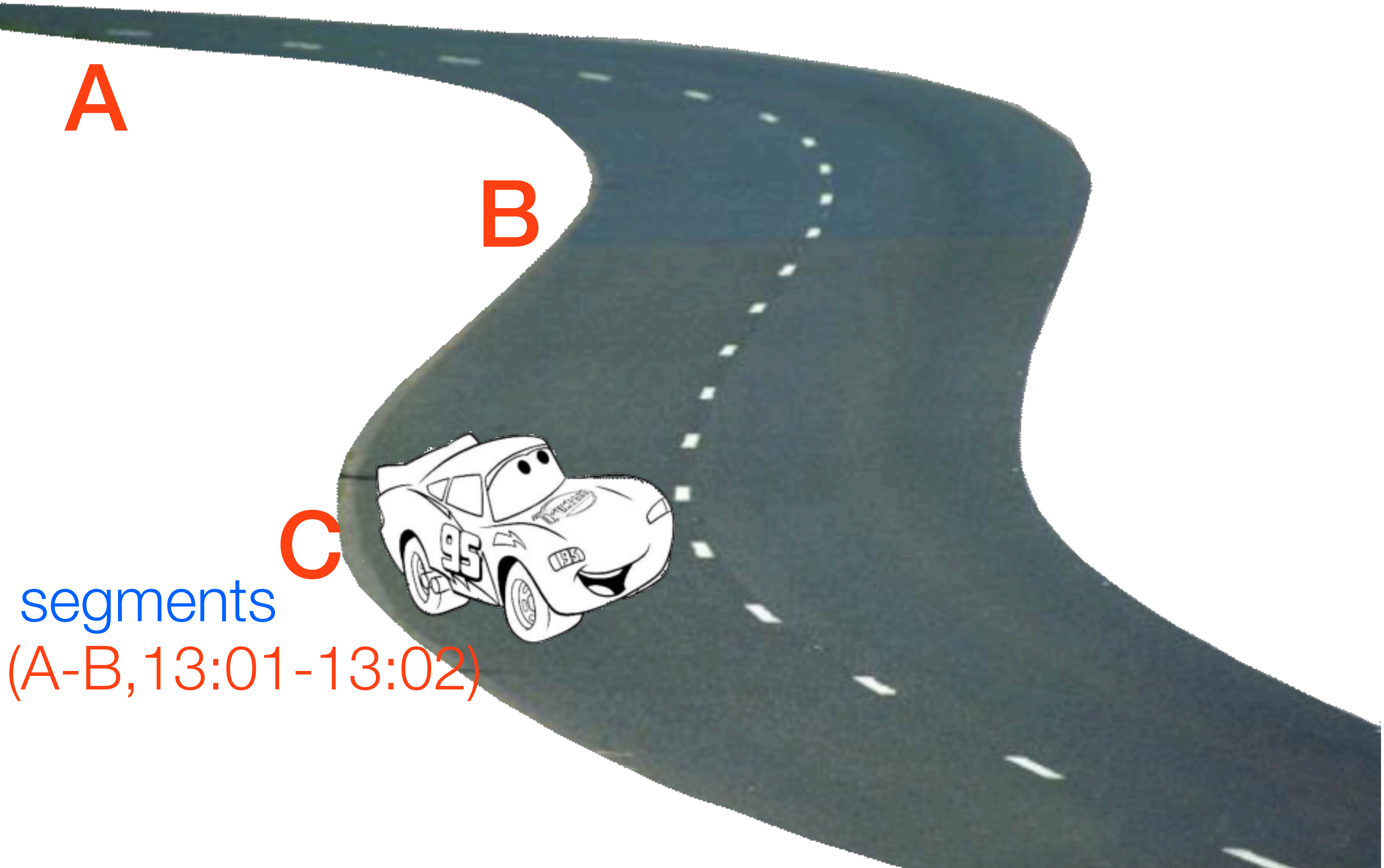
How privacy-preserving toll pricing works



segments

(A-B,13:01-13:02)

How privacy-preserving toll pricing works



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(A-B,13:01-13:02)

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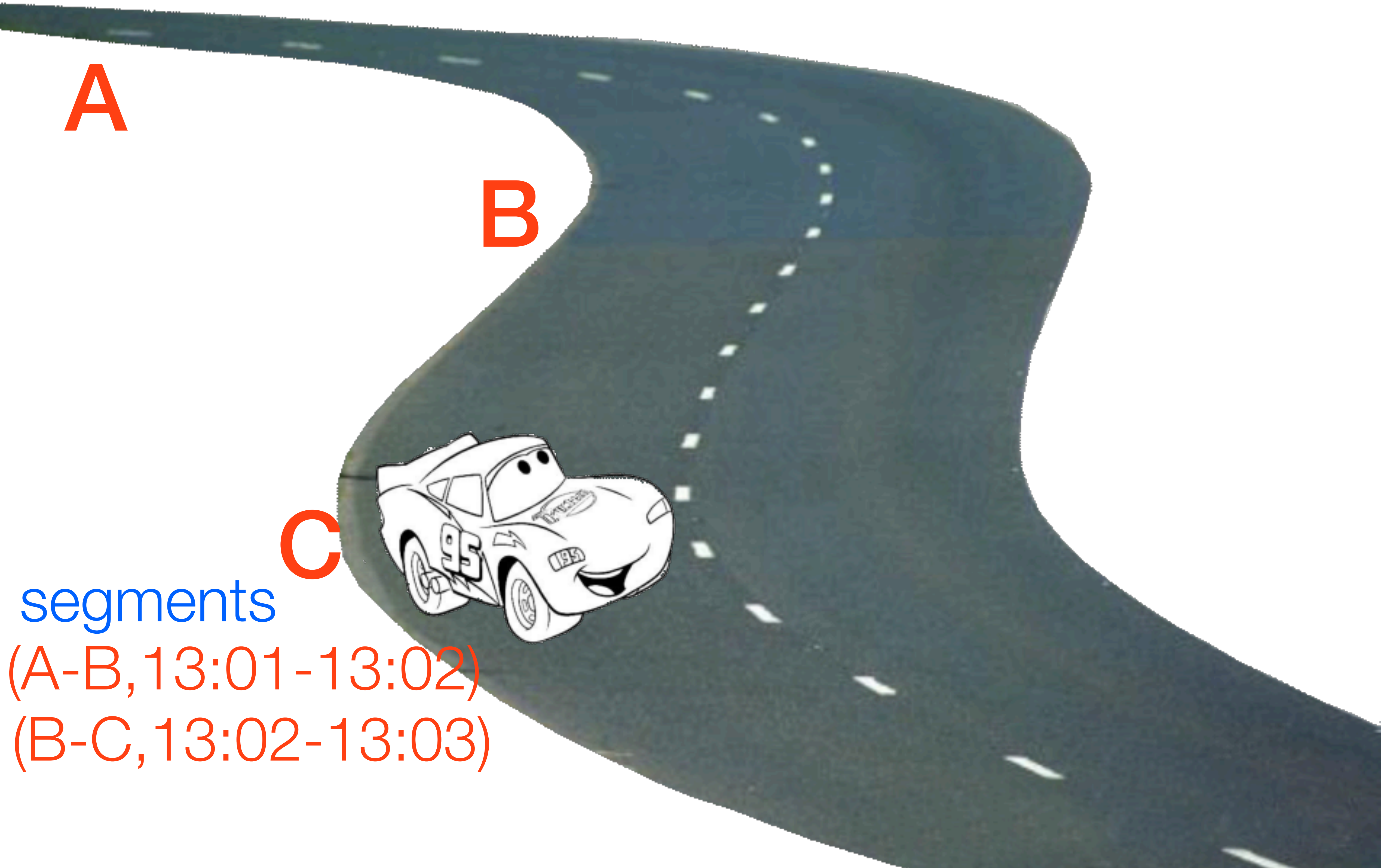

segments

(A-B,13:01-13:02)

(B-C,13:02-13:03)

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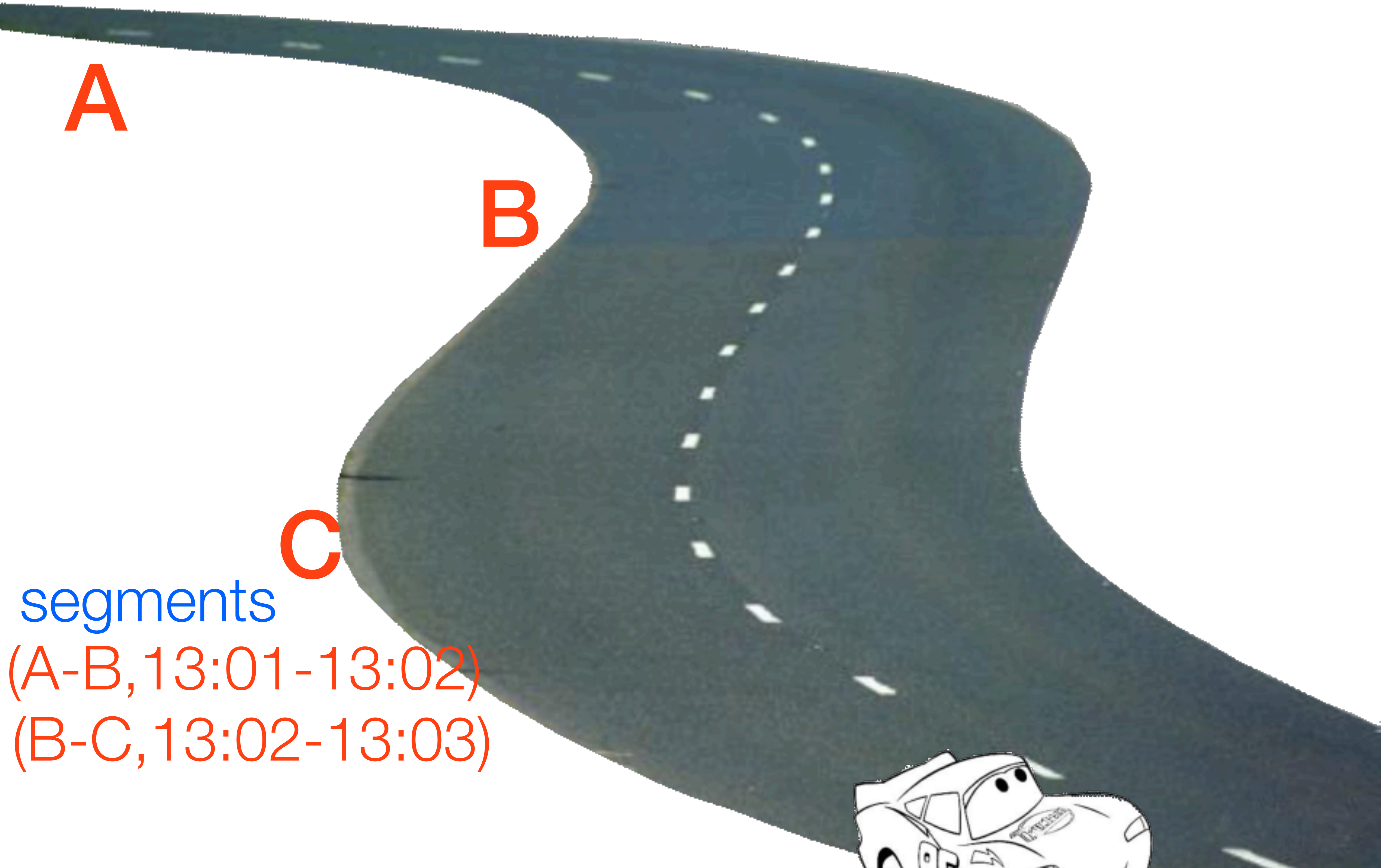

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(A-B,13:01-13:02)

(B-C,13:02-13:03)

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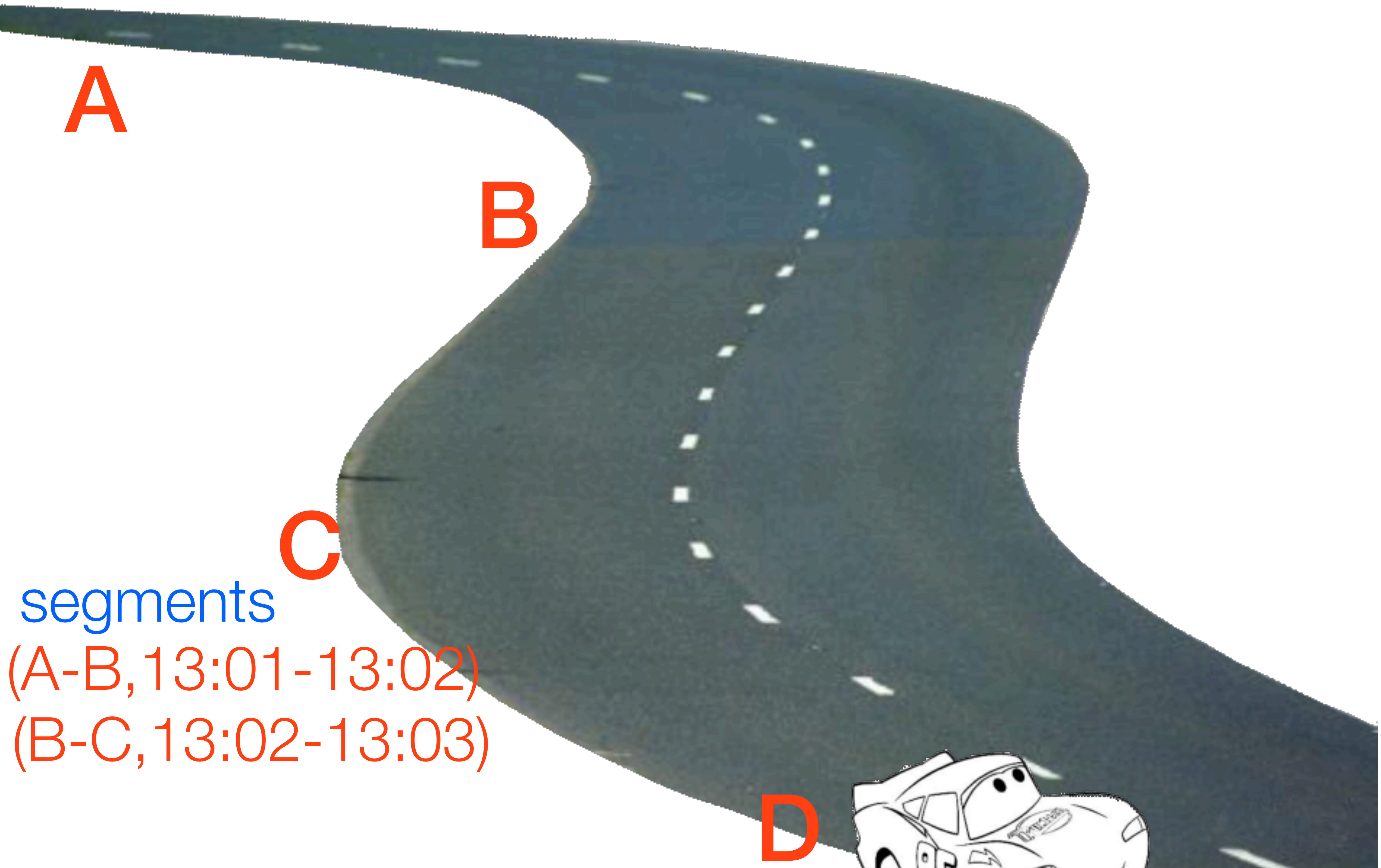
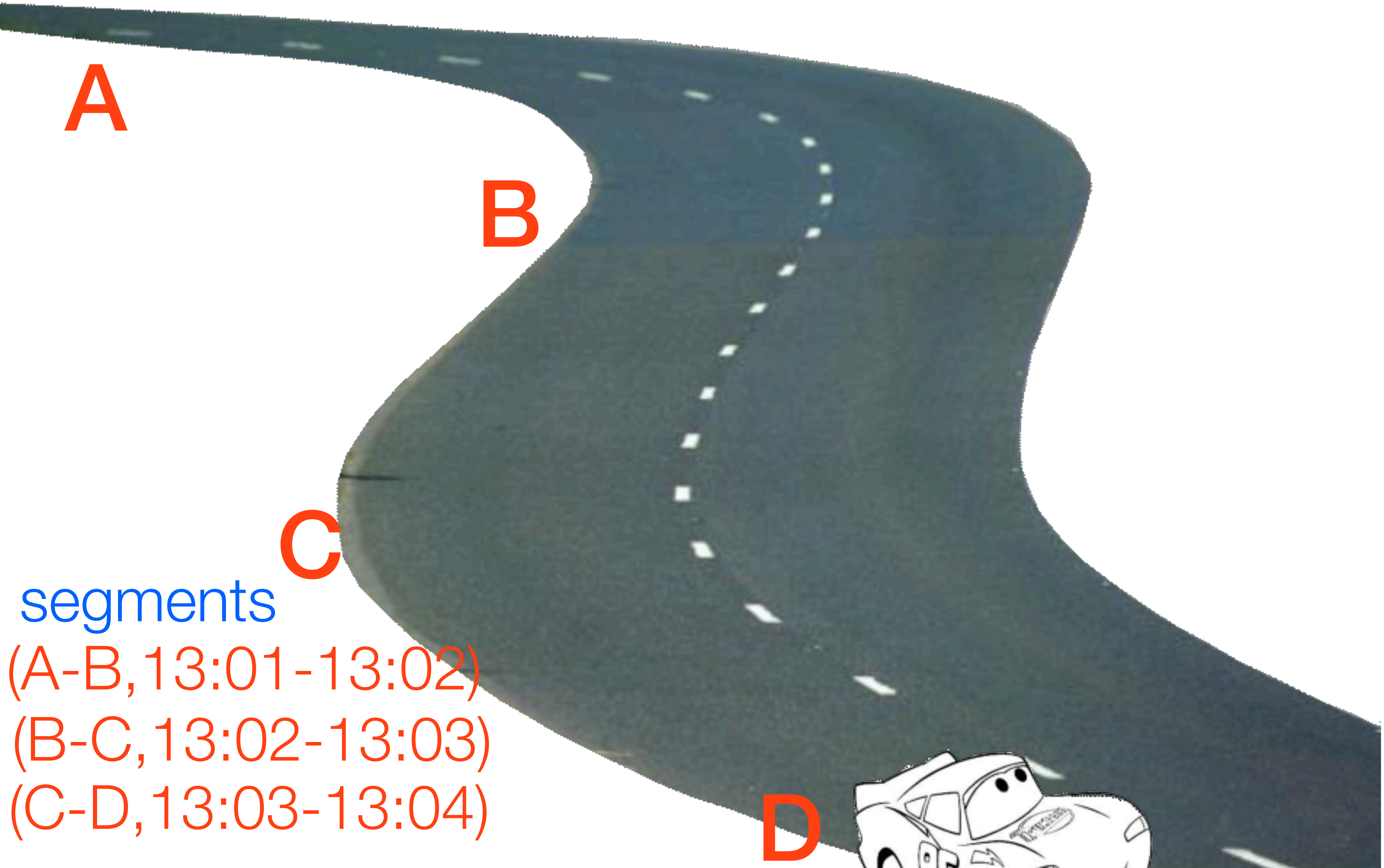


segments

(A-B,13:01-13:02)

(B-C,13:02-13:03)

How privacy-preserving toll pricing works



segments

(A-B,13:01-13:02)

(B-C,13:02-13:03)

(C-D,13:03-13:04)

How privacy-preserving toll pricing works

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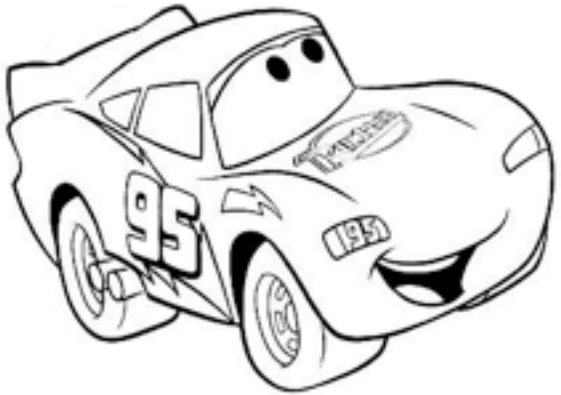
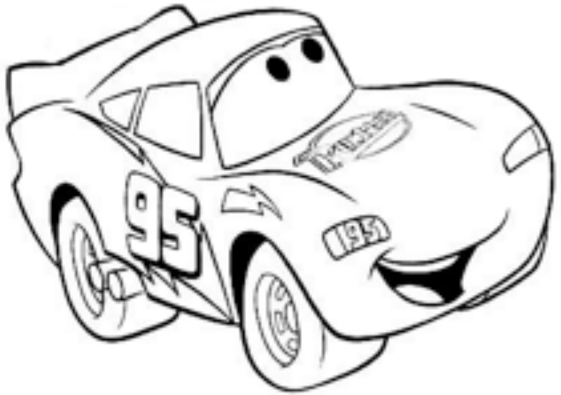


OBU

How privacy-preserving toll pricing works

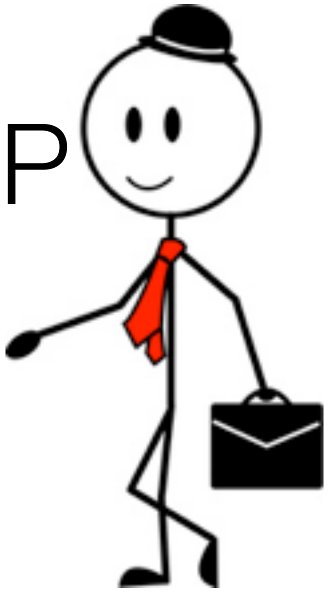


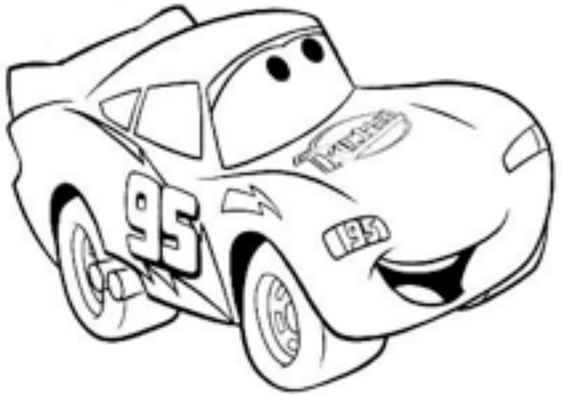
OBU

segments

How privacy-preserving toll pricing works

TSP





OBU

segments

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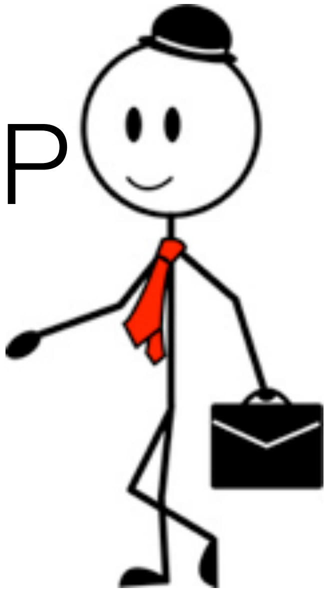
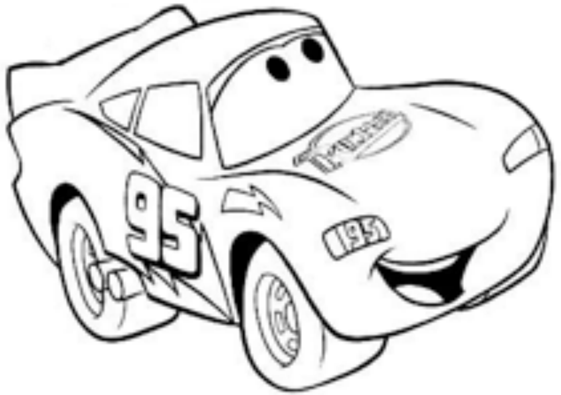


Payment



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segments

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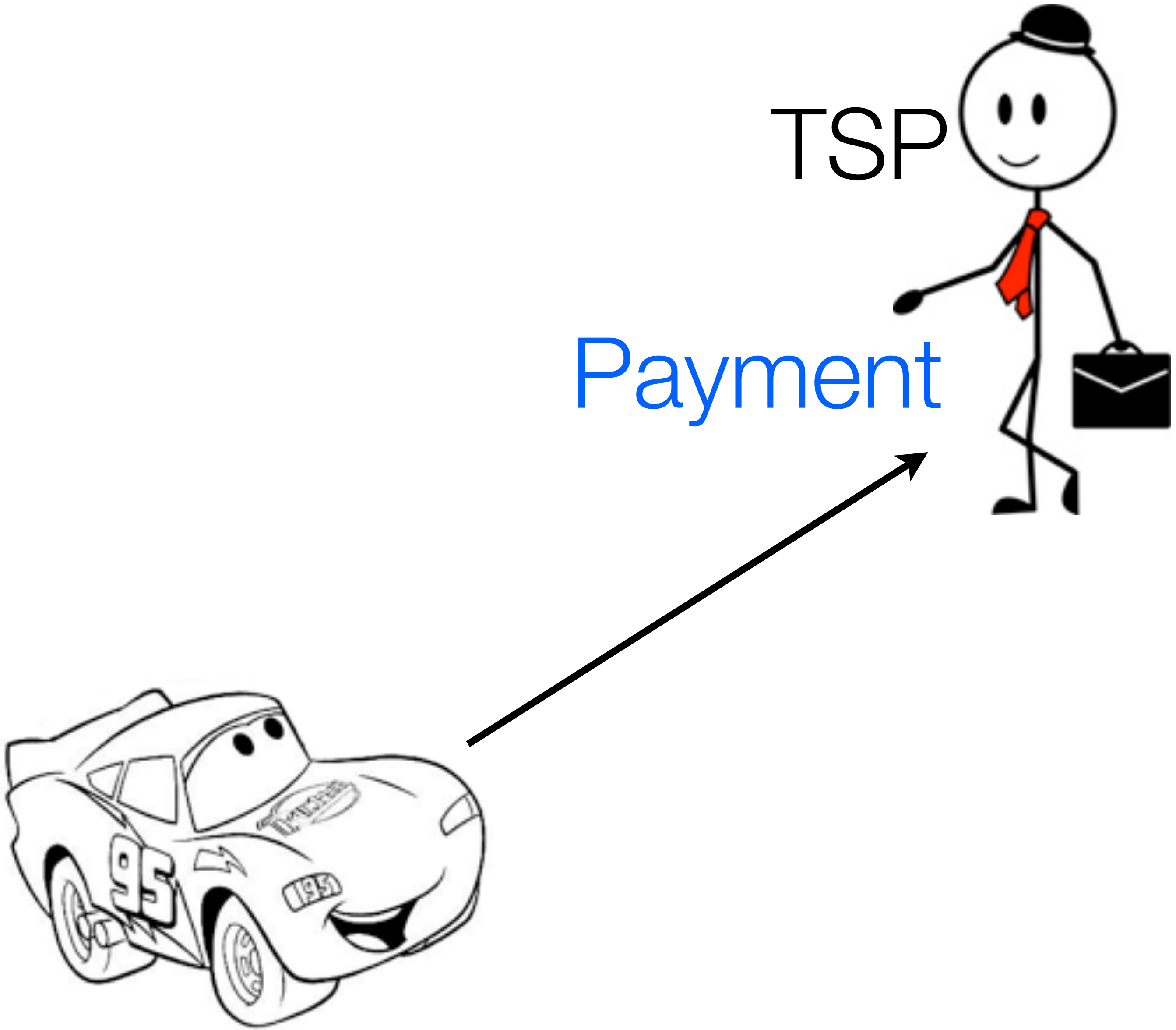


TSP

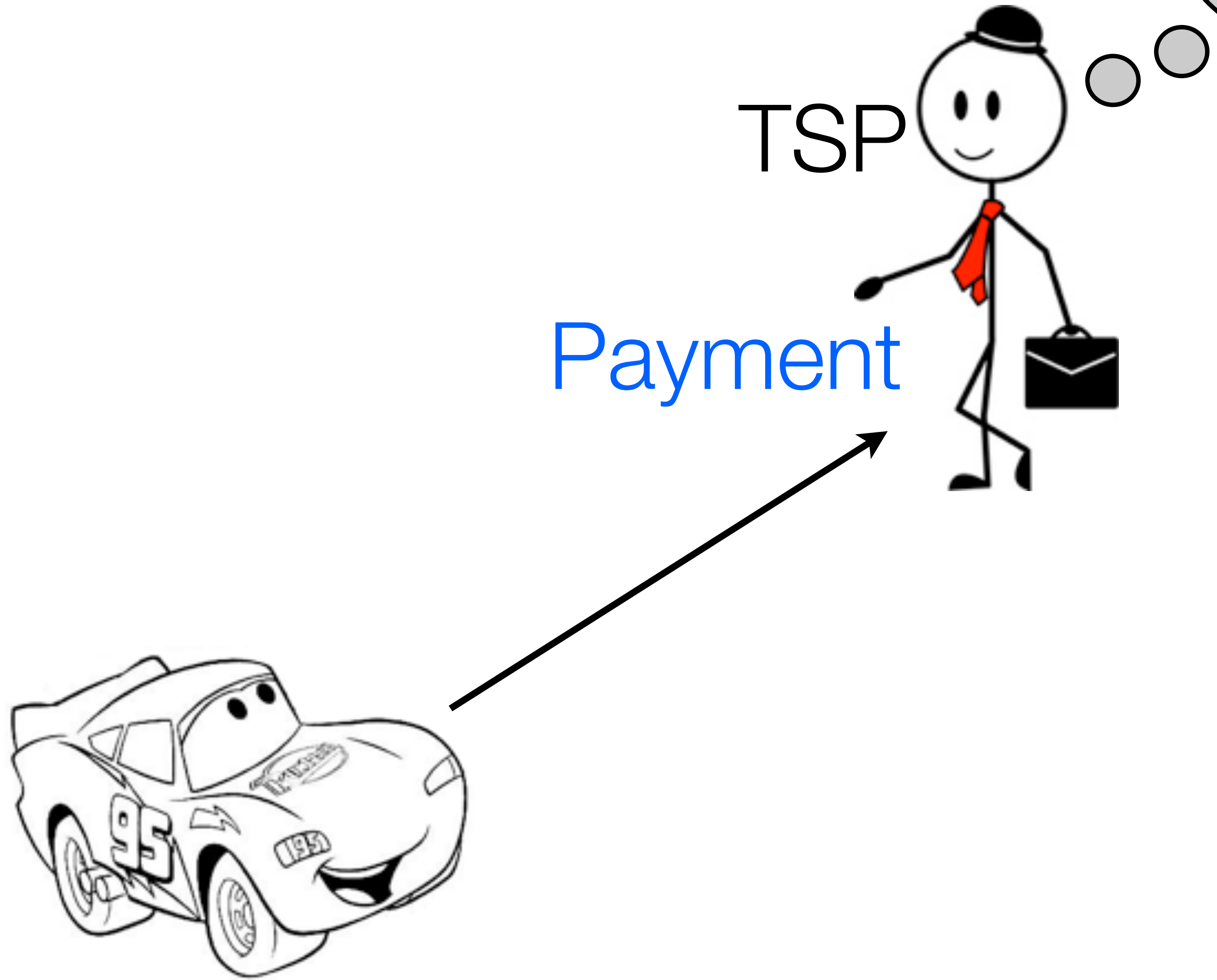
Payment

OBU

segments

How privacy-preserving toll

Check information and charge driver what they owe



TSP

Payment

OBU

segments

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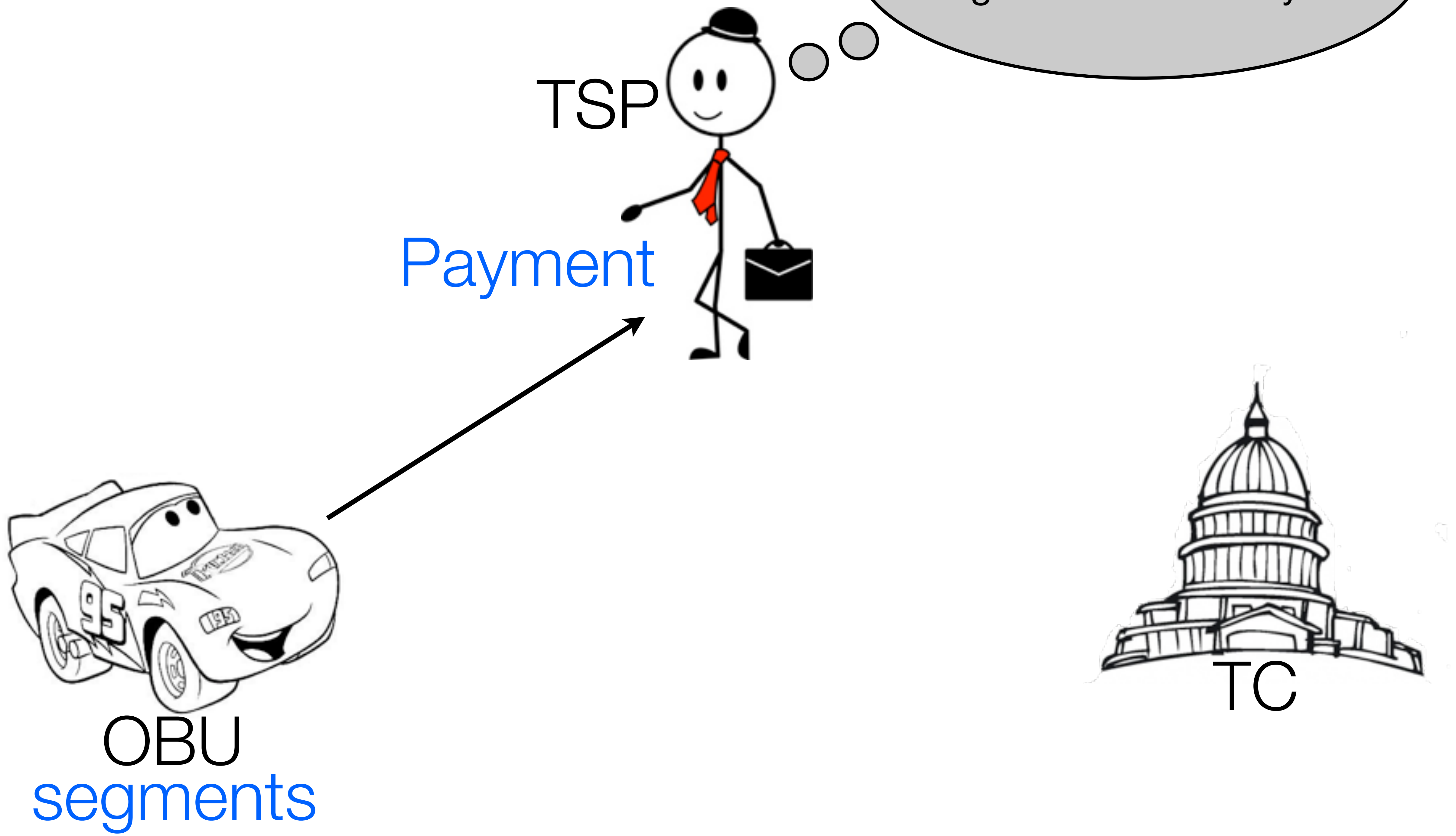


TSP

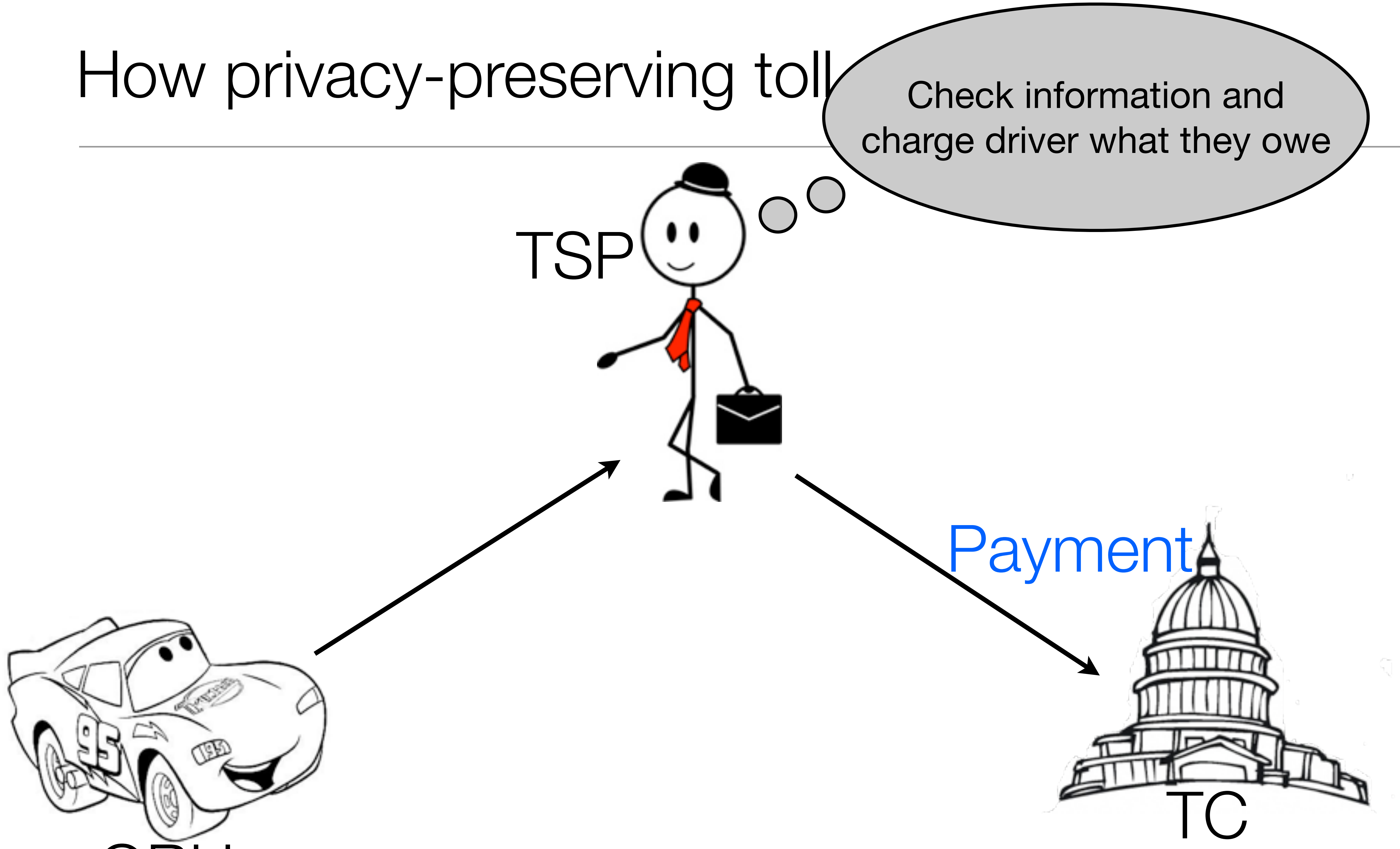
Payment

OBU

segments

TC

How privacy-preserving toll



Check information and charge driver what they owe

TSP

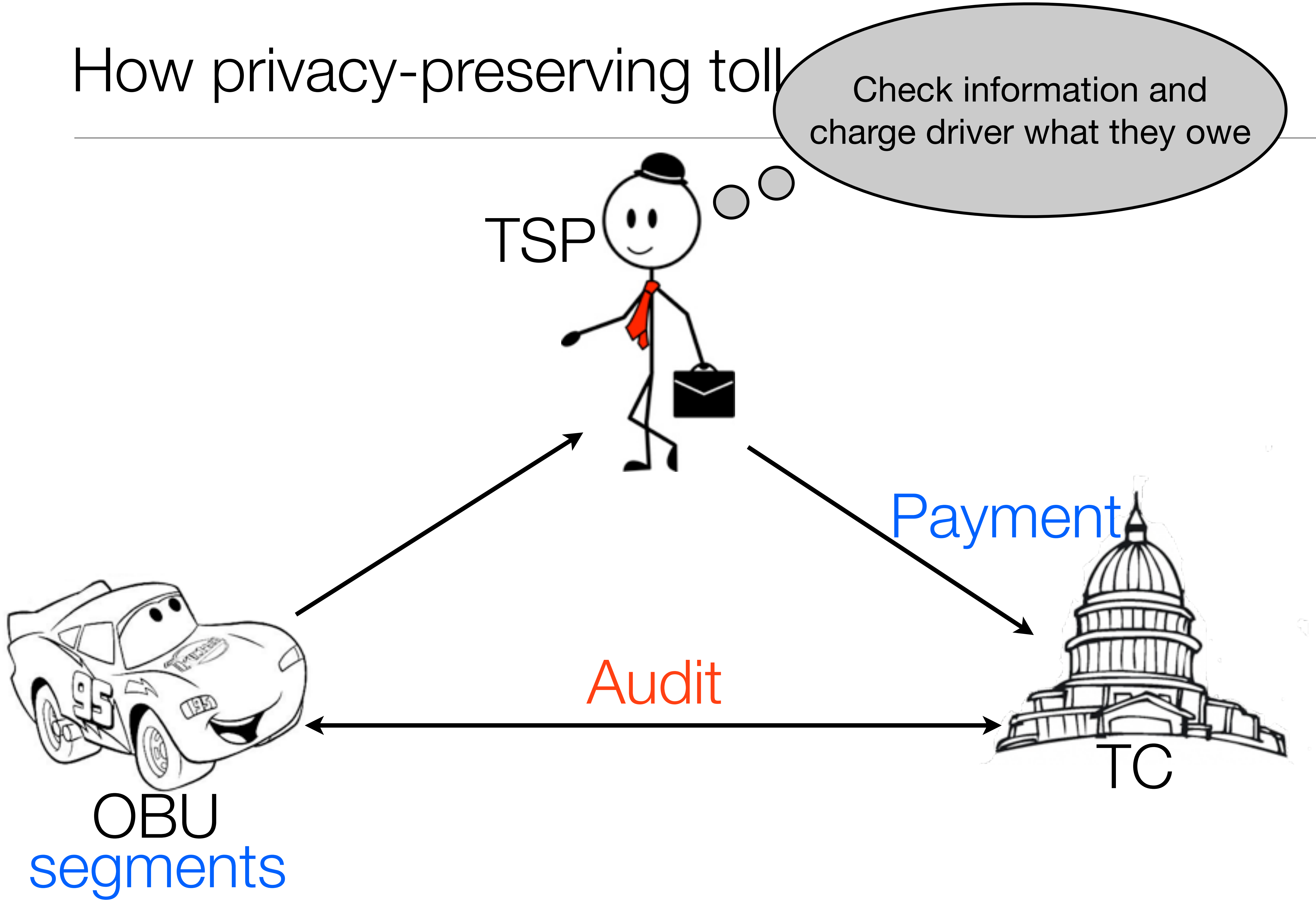
Payment

TC

OBU

segments

How privacy-preserving toll



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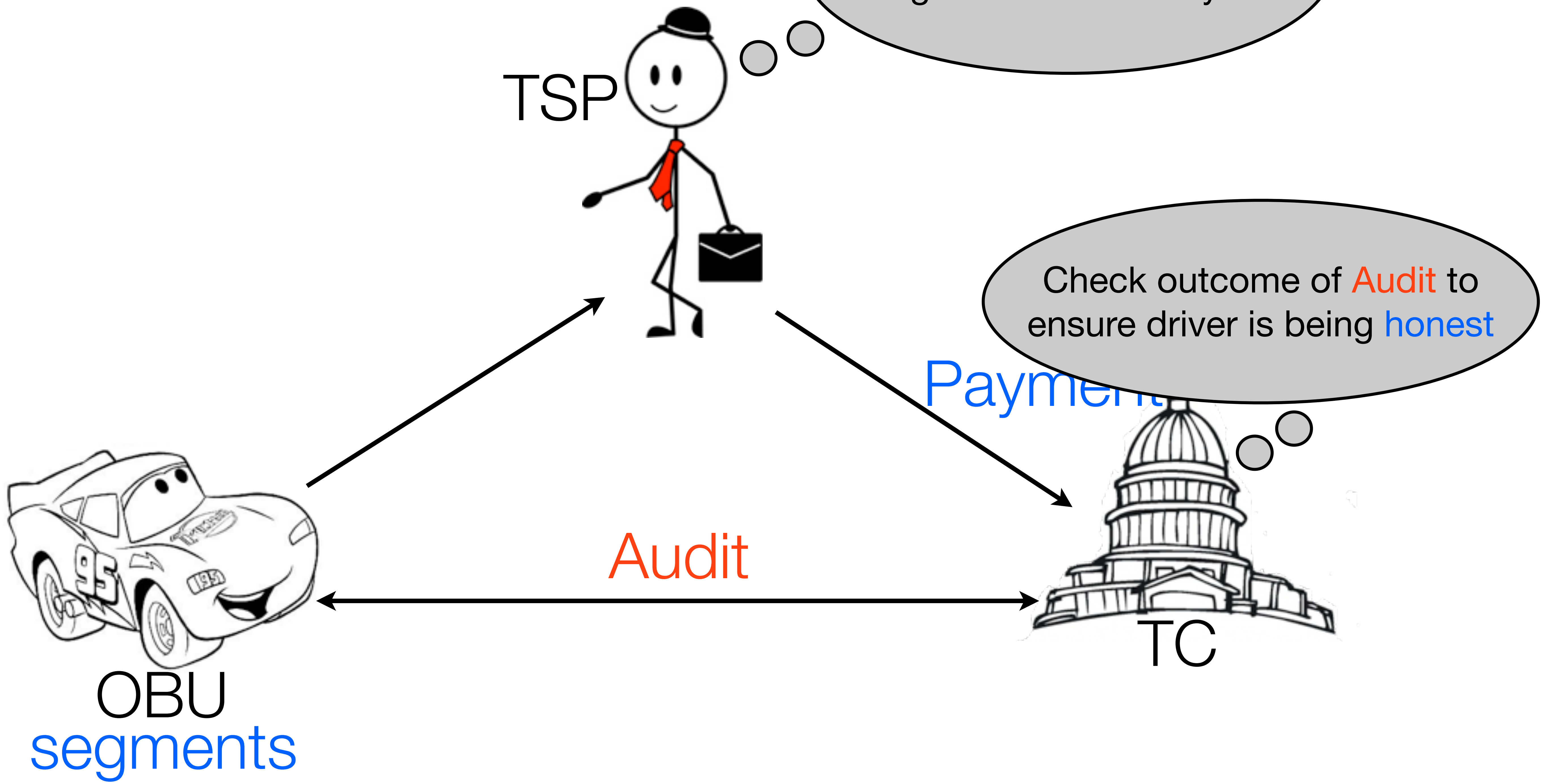
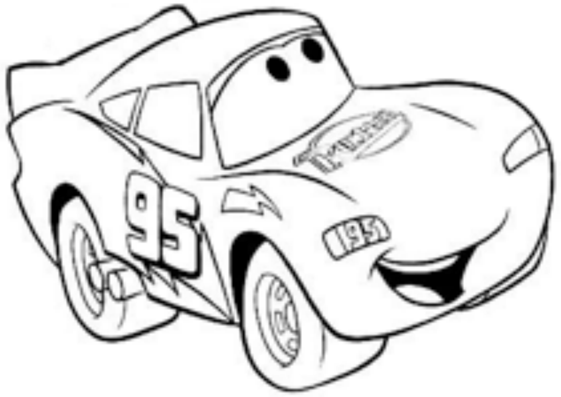
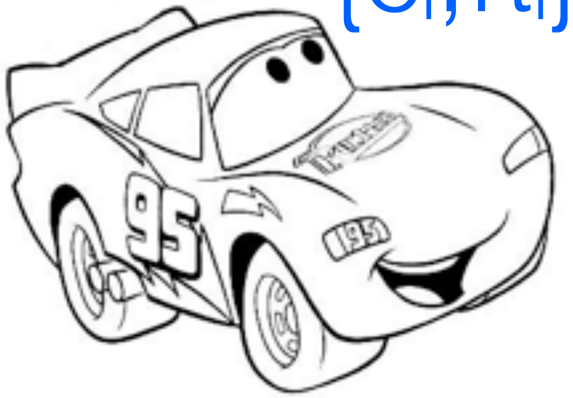


An adapted version of PrETP



An adapted version of PrETP

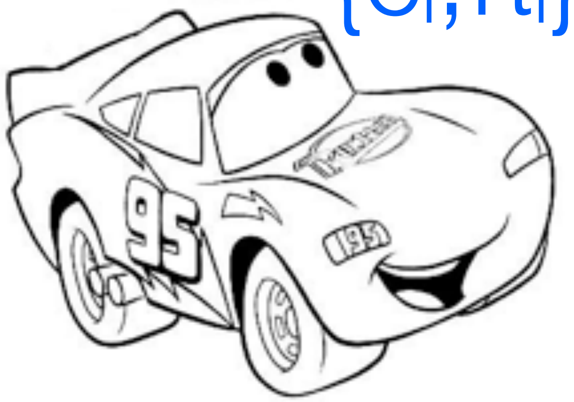
$\{c_i,\pi_i\}_i$



An adapted version of PrETP

Commitment to segment price p_i

$\{c_i, \pi_i\}_i$

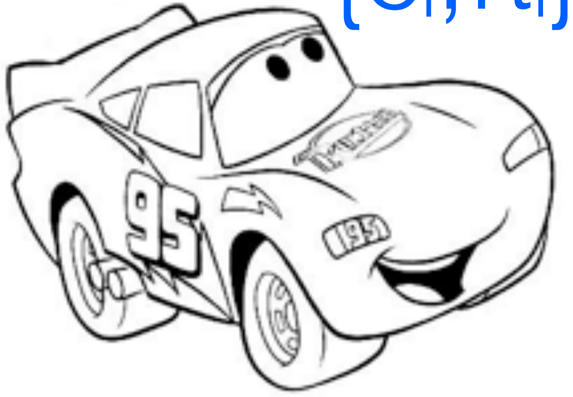


An adapted version of PrETP

Commitment to segment price p_i

NIZK that the value in c_i is in the proper range

$\{c_i, \pi_i\}_i$



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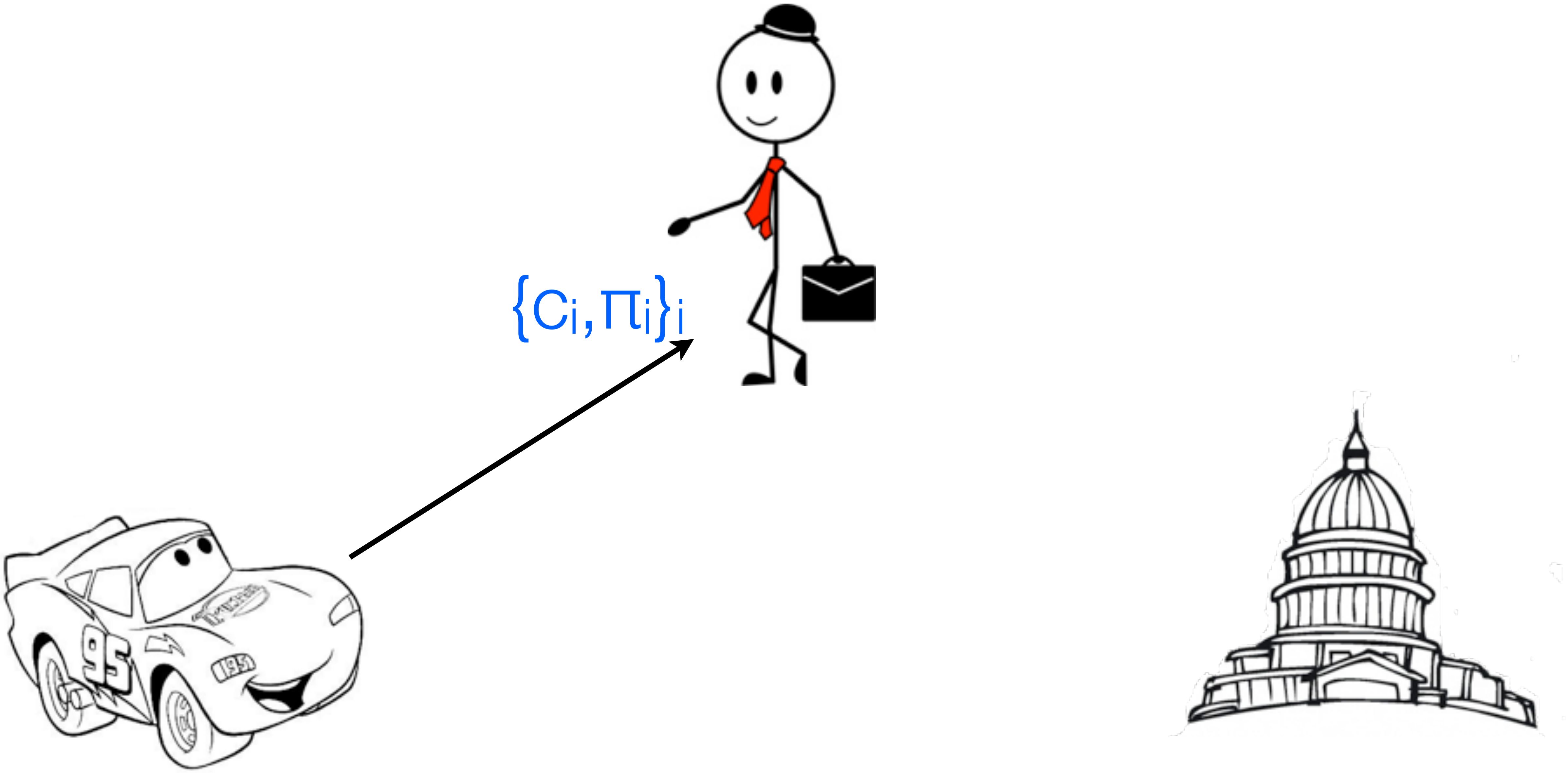

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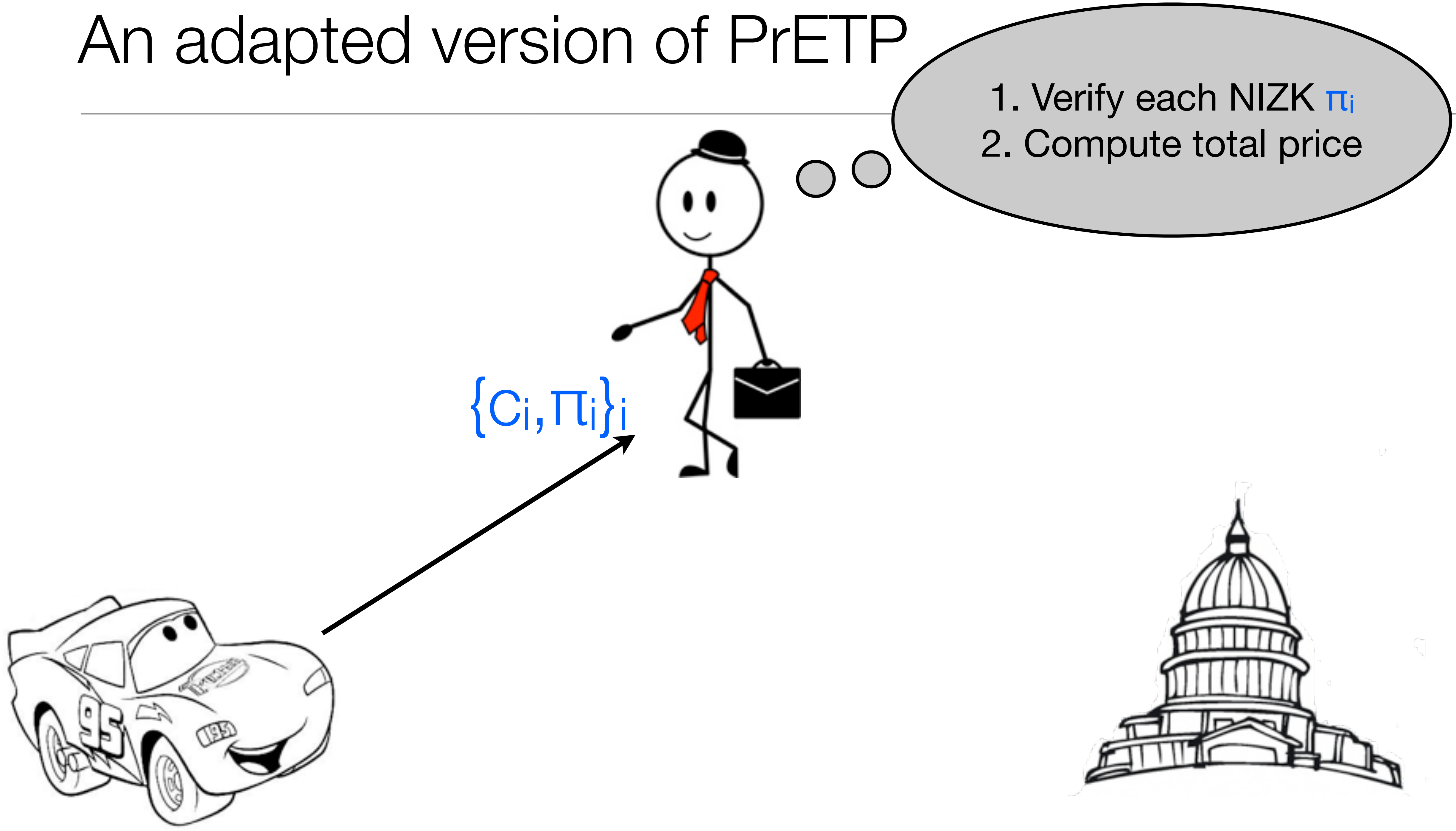
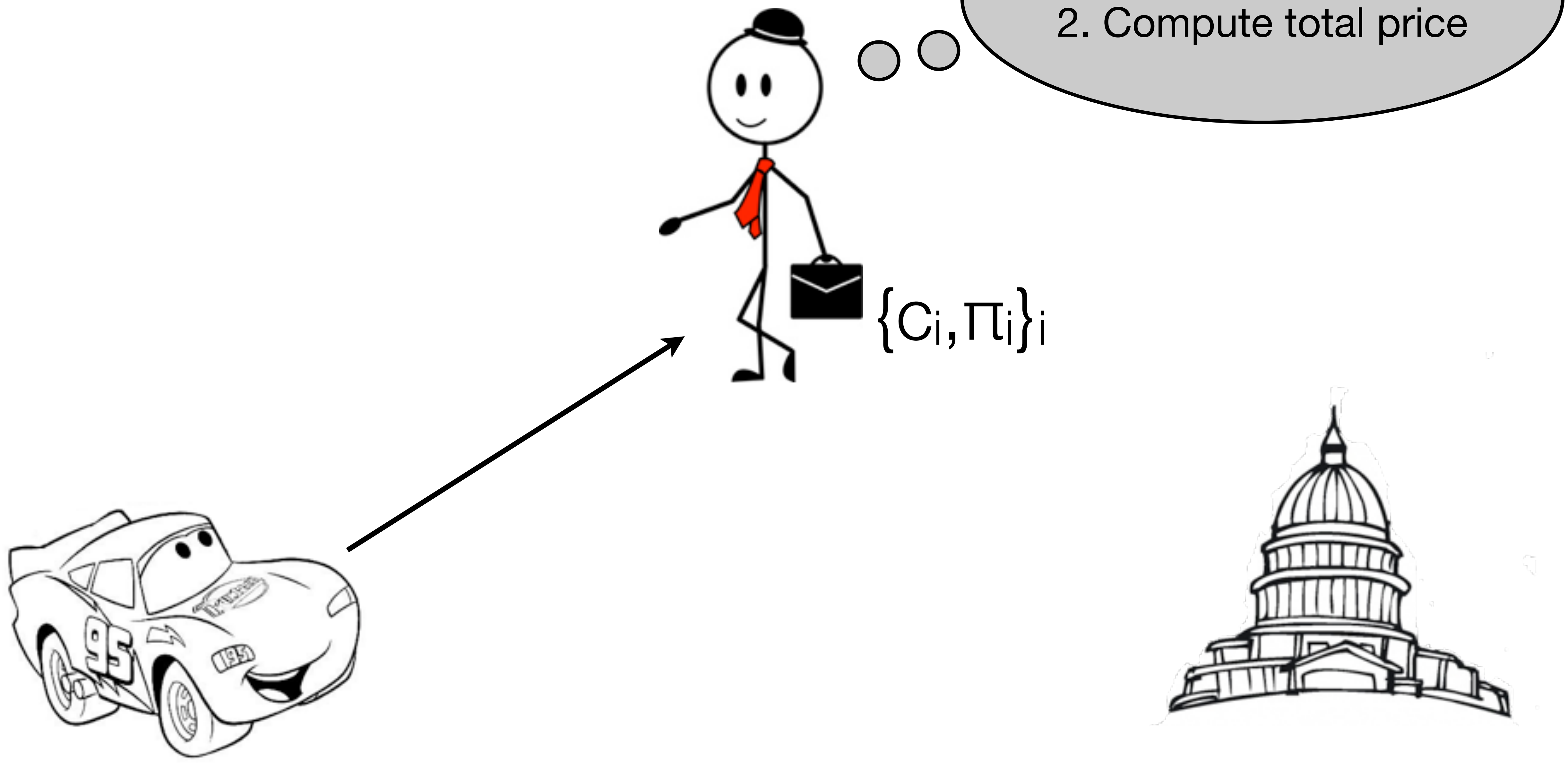


1. Verify each NIZK π_i
2. Compute total price

$\{c_i, \pi_i\}_i$

An adapted version of PrETP



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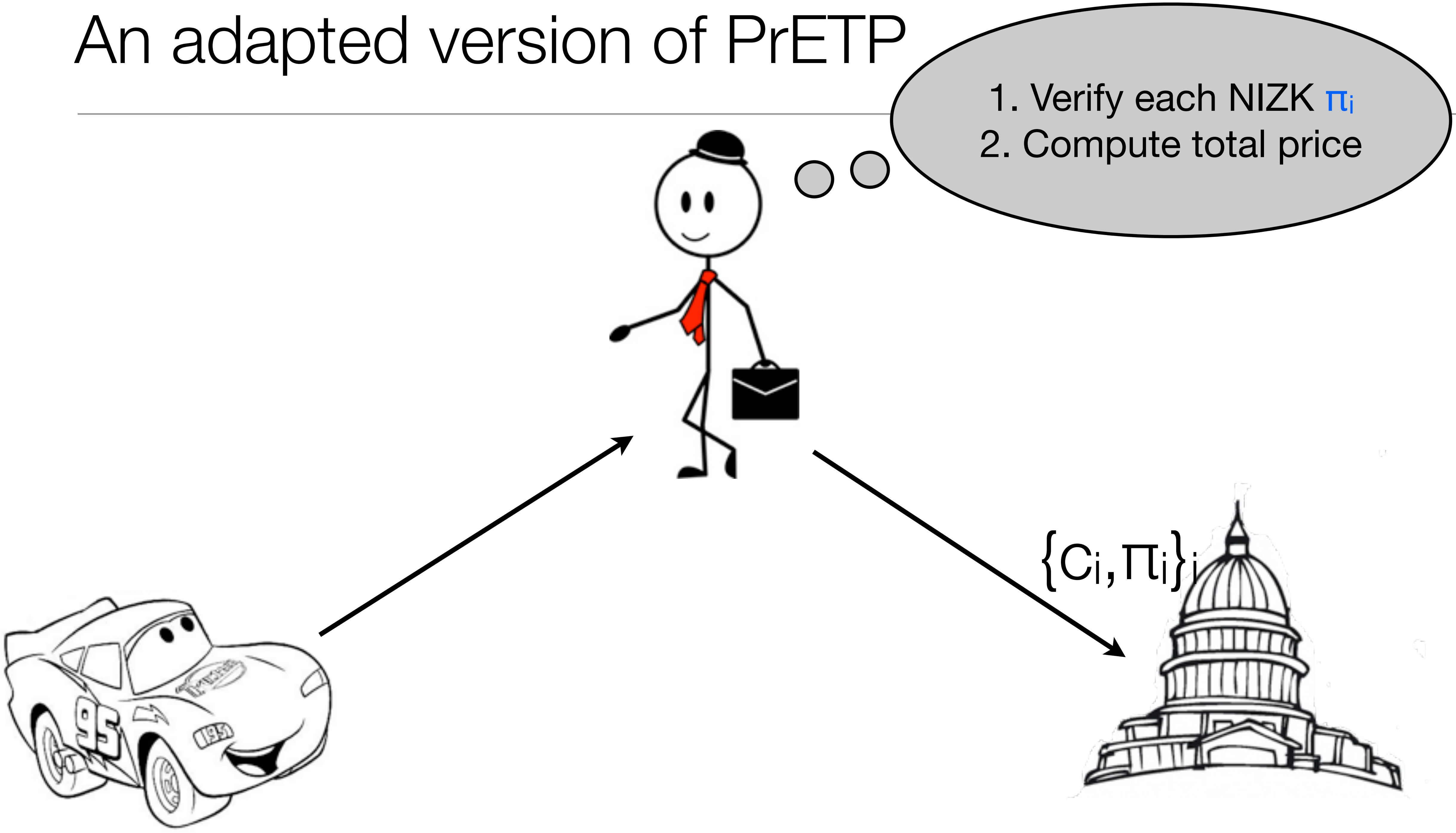

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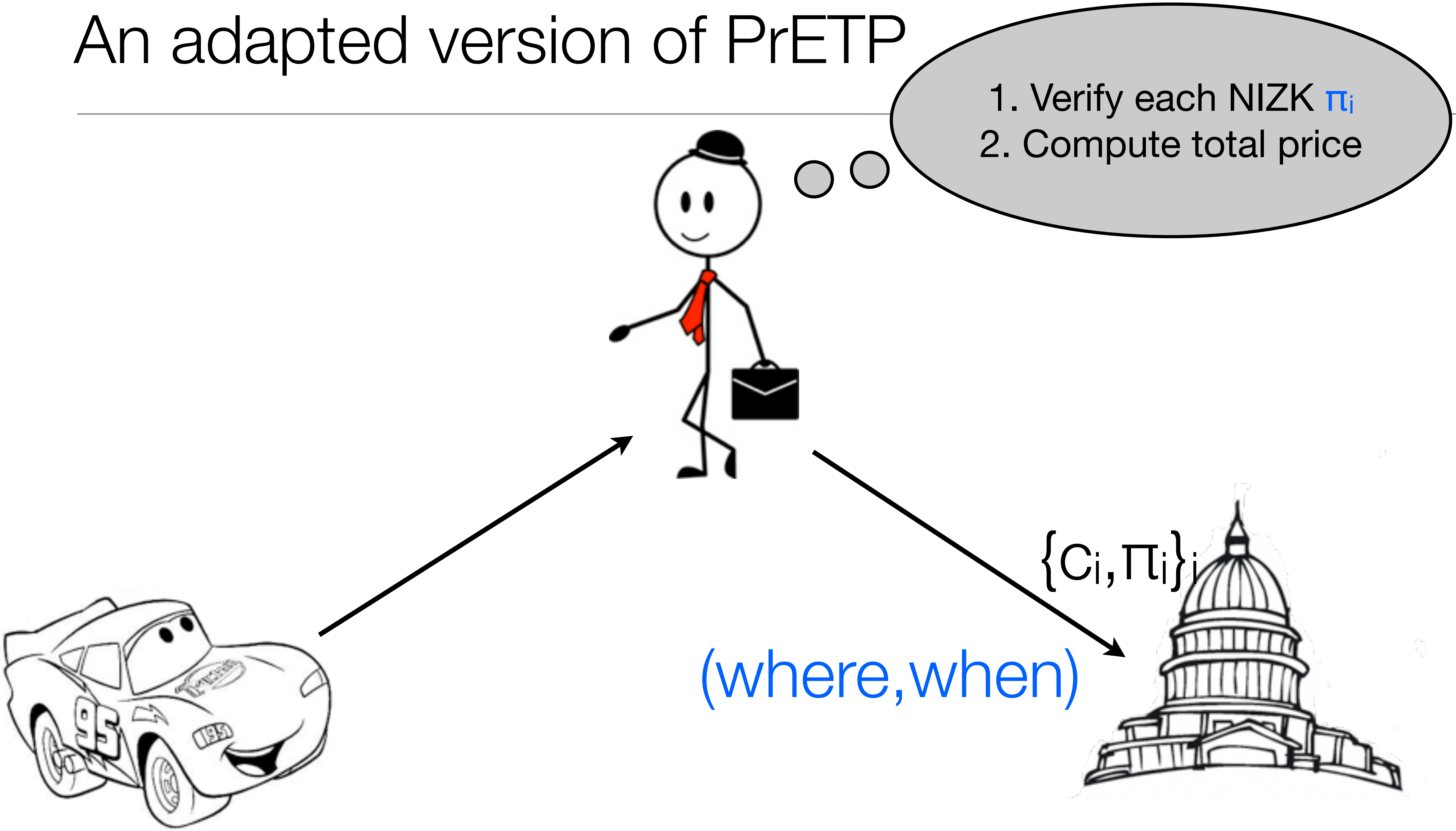

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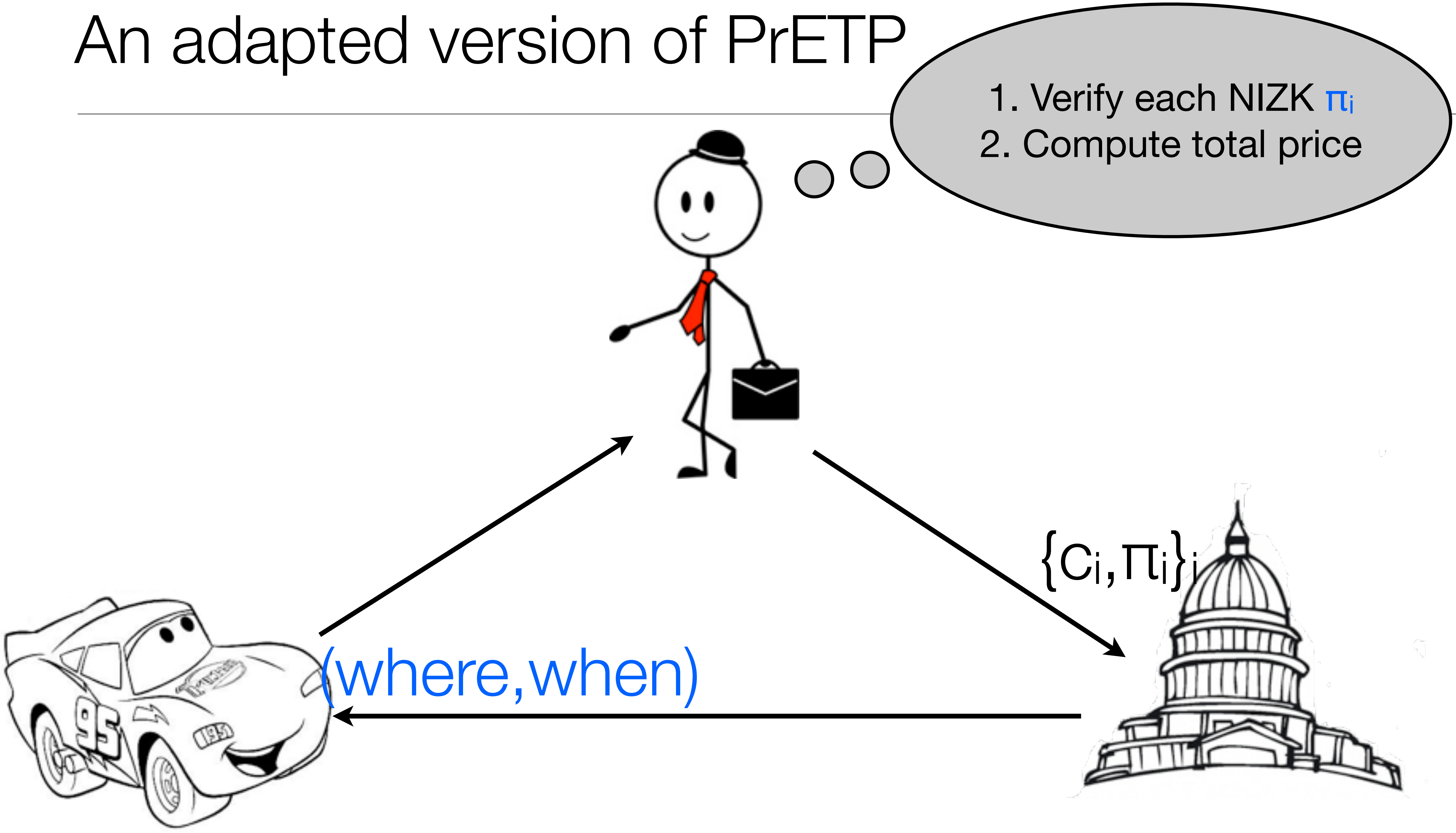
$\{c_i,\pi_i\}_i$

(where,when)

An adapted version of PrETP



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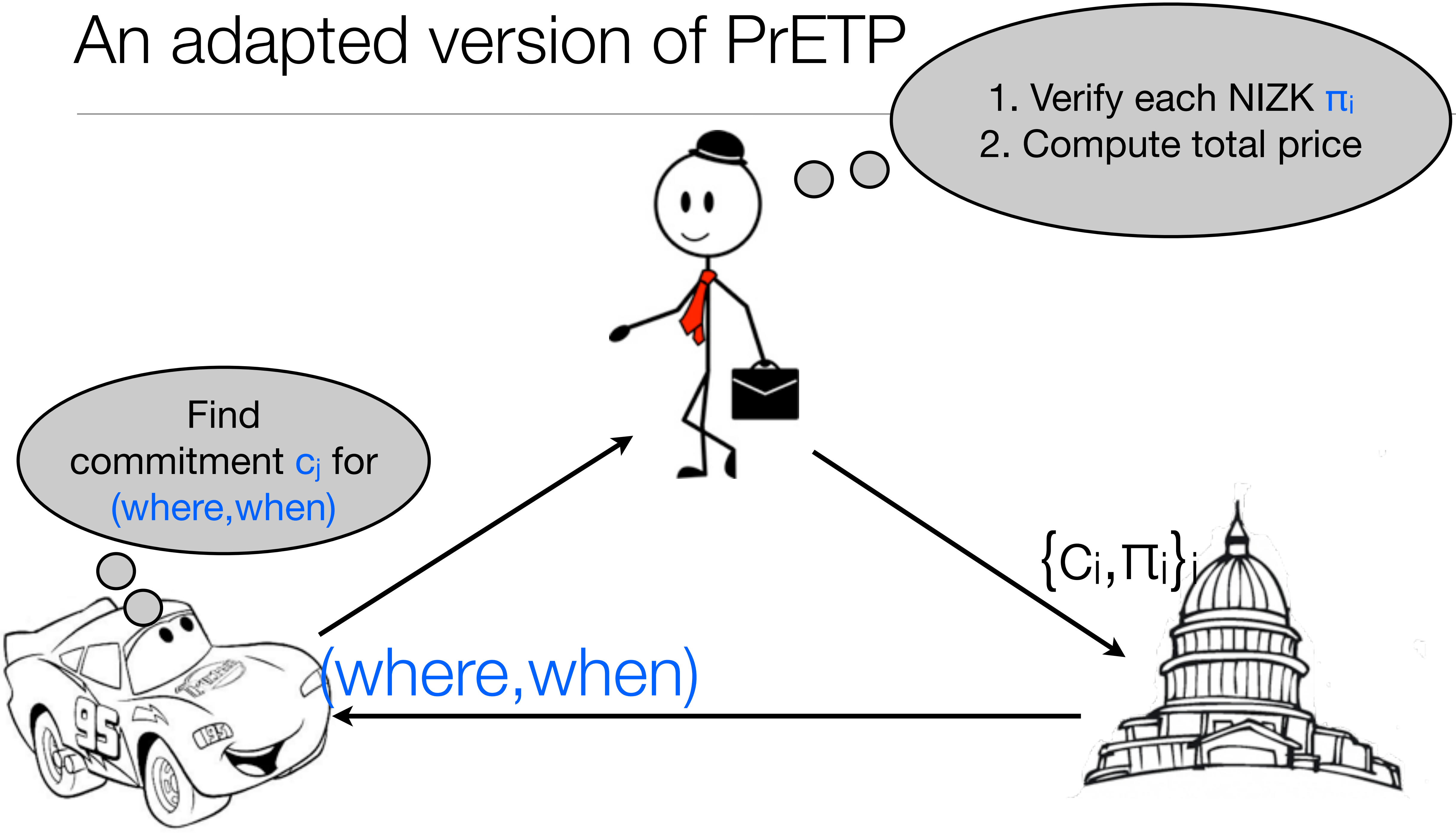
An adapted version of PrETP



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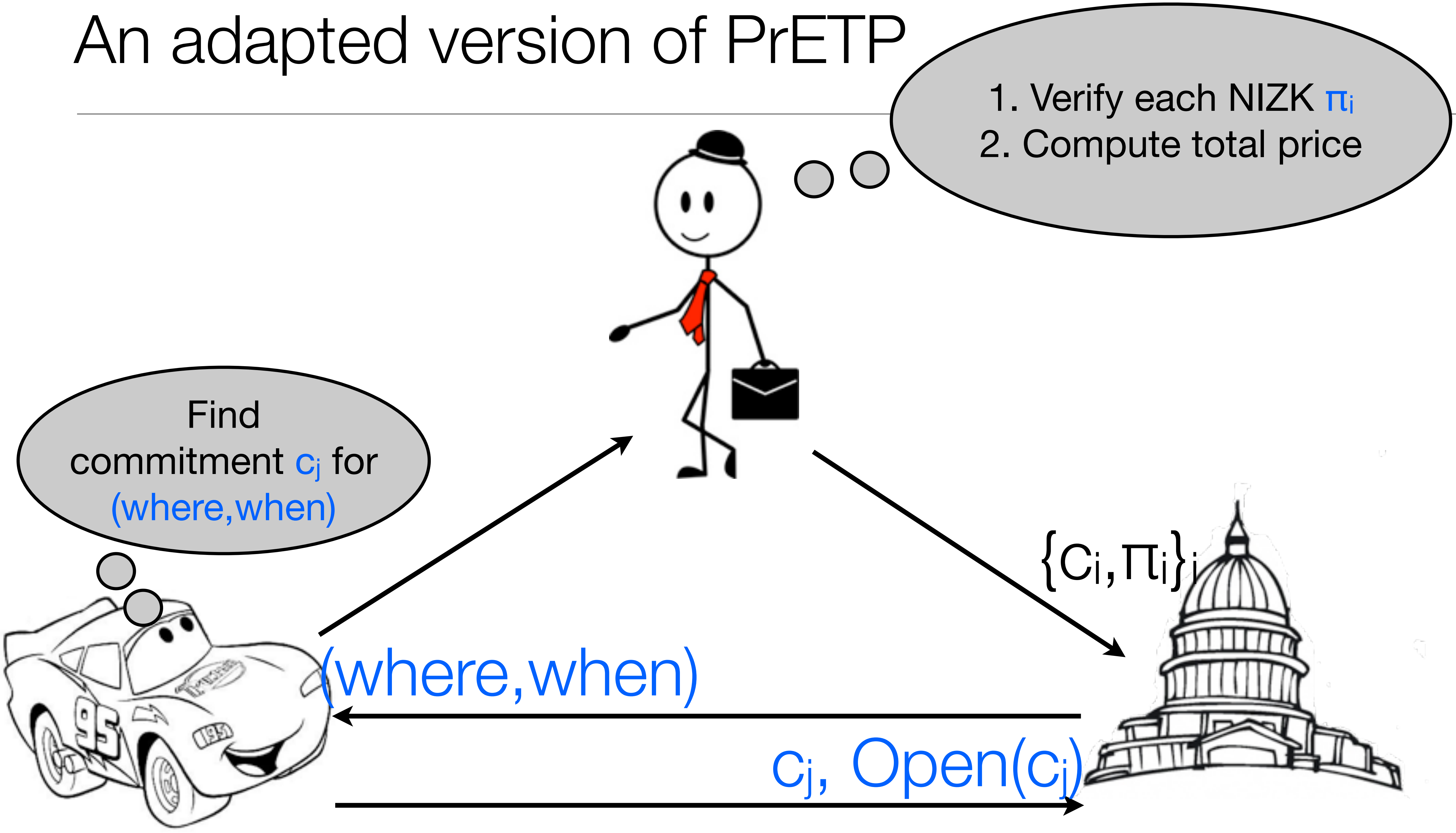
Find commitment c_j for (where,when)

$\{c_i,\pi_i\}_i$

(where,when)

An adapted version of PrETP



1. Verify each NIZK π_i
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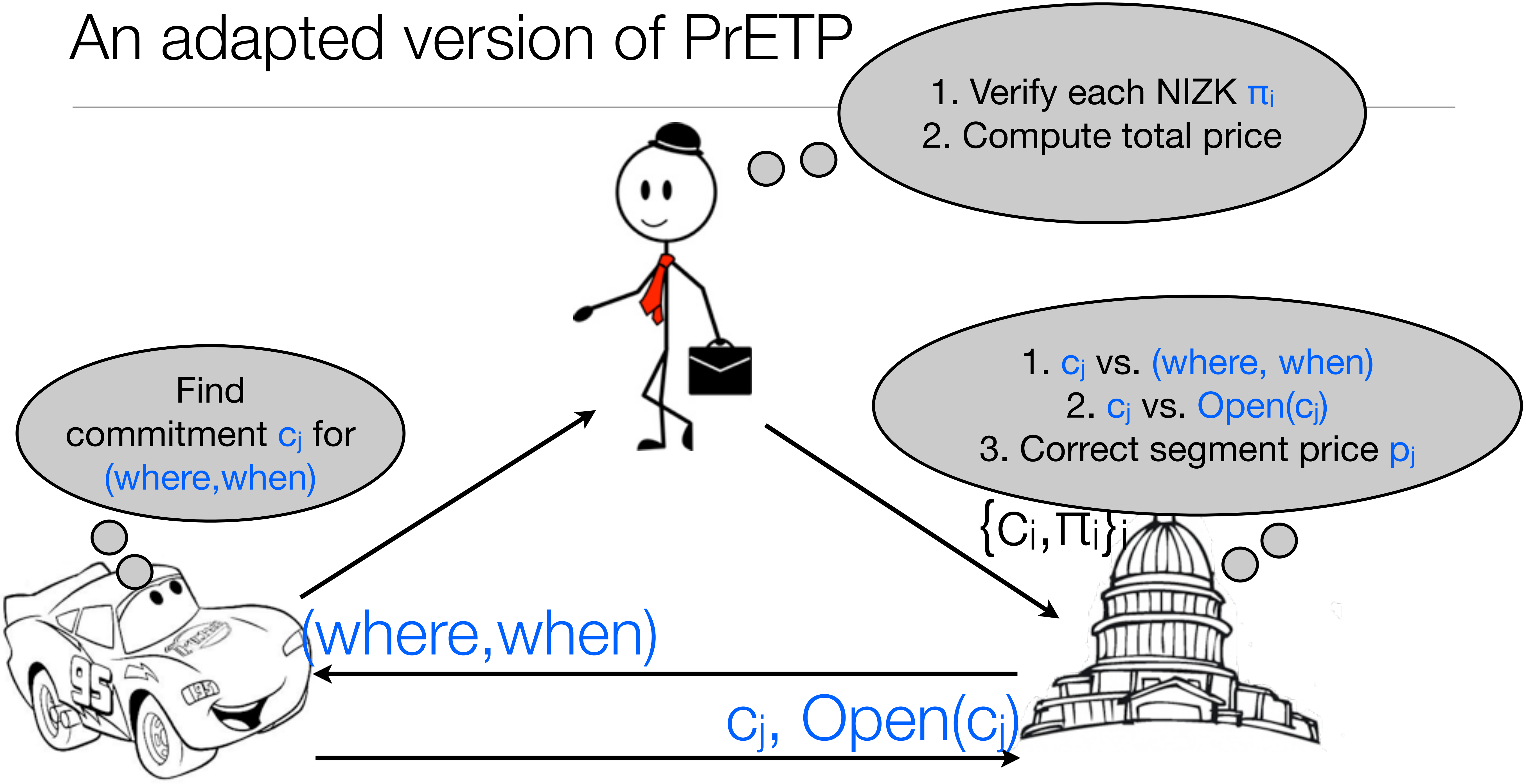
Find commitment c_j for (where,when)

$\{c_i, \pi_i\}_i$

(where,when)

c_j, Open(c_j)

An adapted version of PrETP



1. Verify each NIZK π_i
2. Compute total price

Find commitment c_j for (where,when)

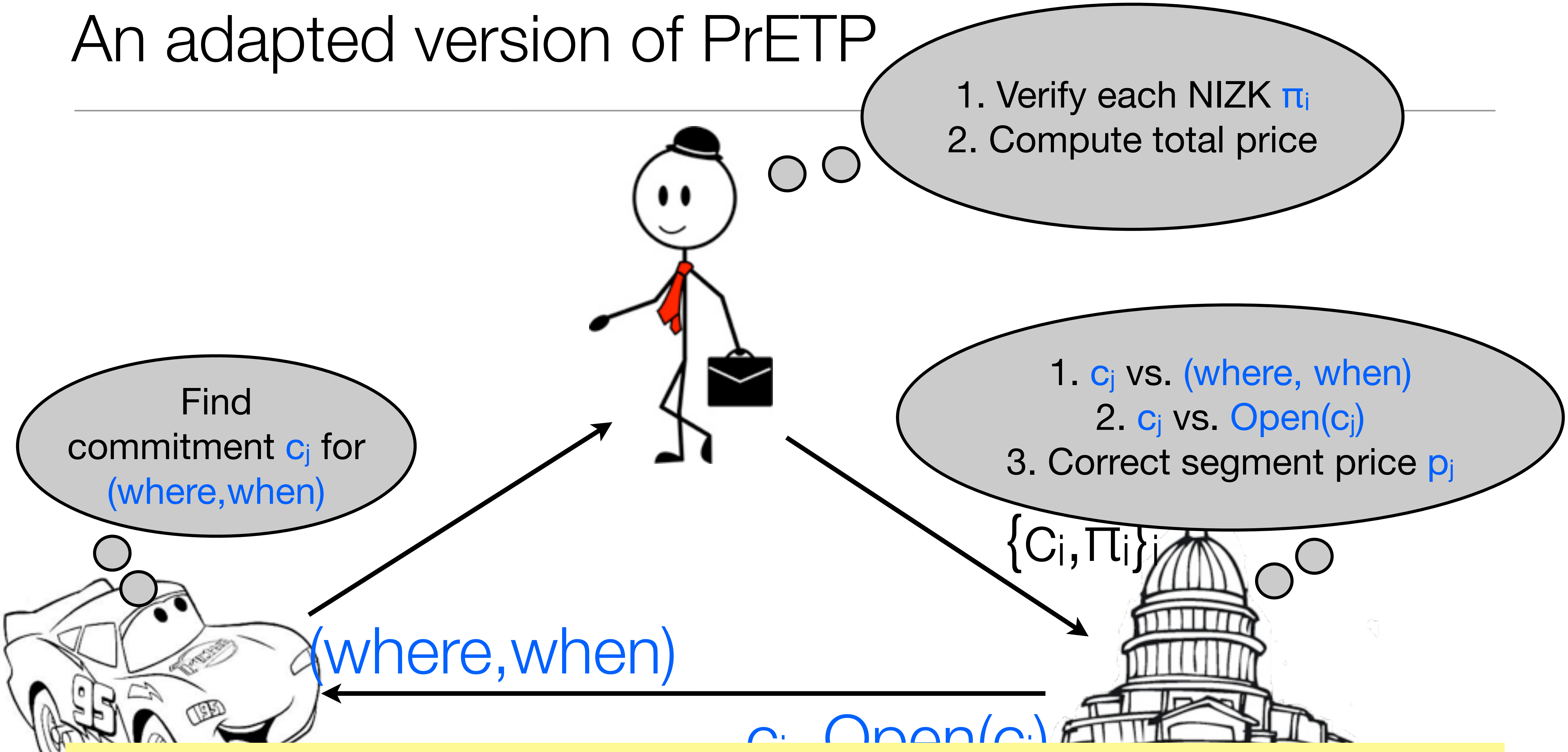
1. c_j vs. (where, when)
2. c_j vs. Open(c_j)
3. Correct segment price p_j

$\{c_i,\pi_i\}_i$

(where,when)

c_j, Open(c_j)

An adapted version of PrETP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1. c_j vs. (where, when)
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$\{c_i,\pi_i\}_i$
(where,when)
c_j, Open(c_j)

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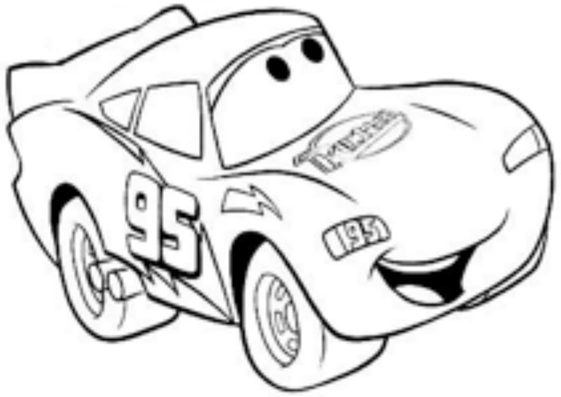
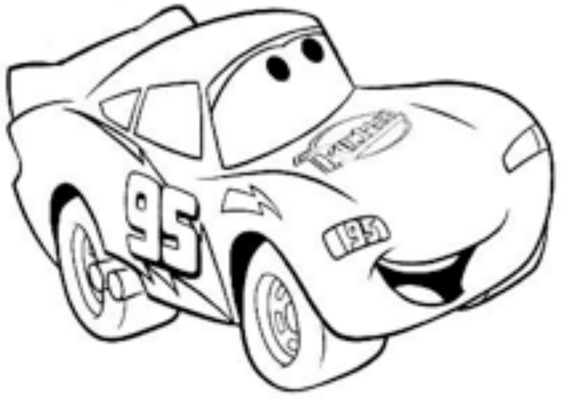
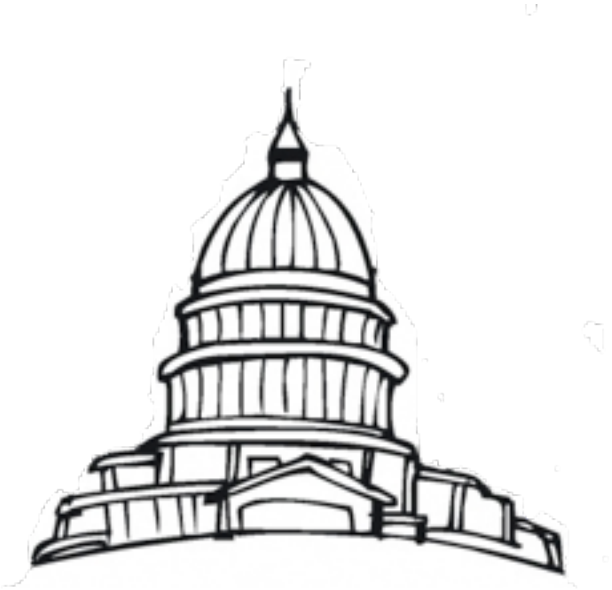
“PrETP with sugar on top”: our new Audit protocol



“PrETP with sugar on top”: our new Audit protocol

$\{c_i, C_i, \pi_i\}_i$

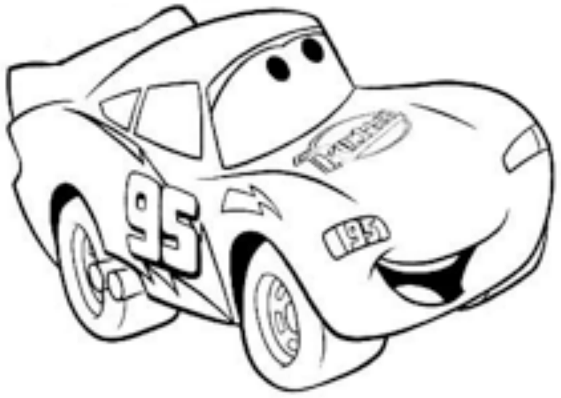




“PrETP with sugar on top”: our new Audit protocol

Blind IBE of the opening to c_i, using (where,when) as identity

$\{c_i, C_i, \pi_i\}_i$



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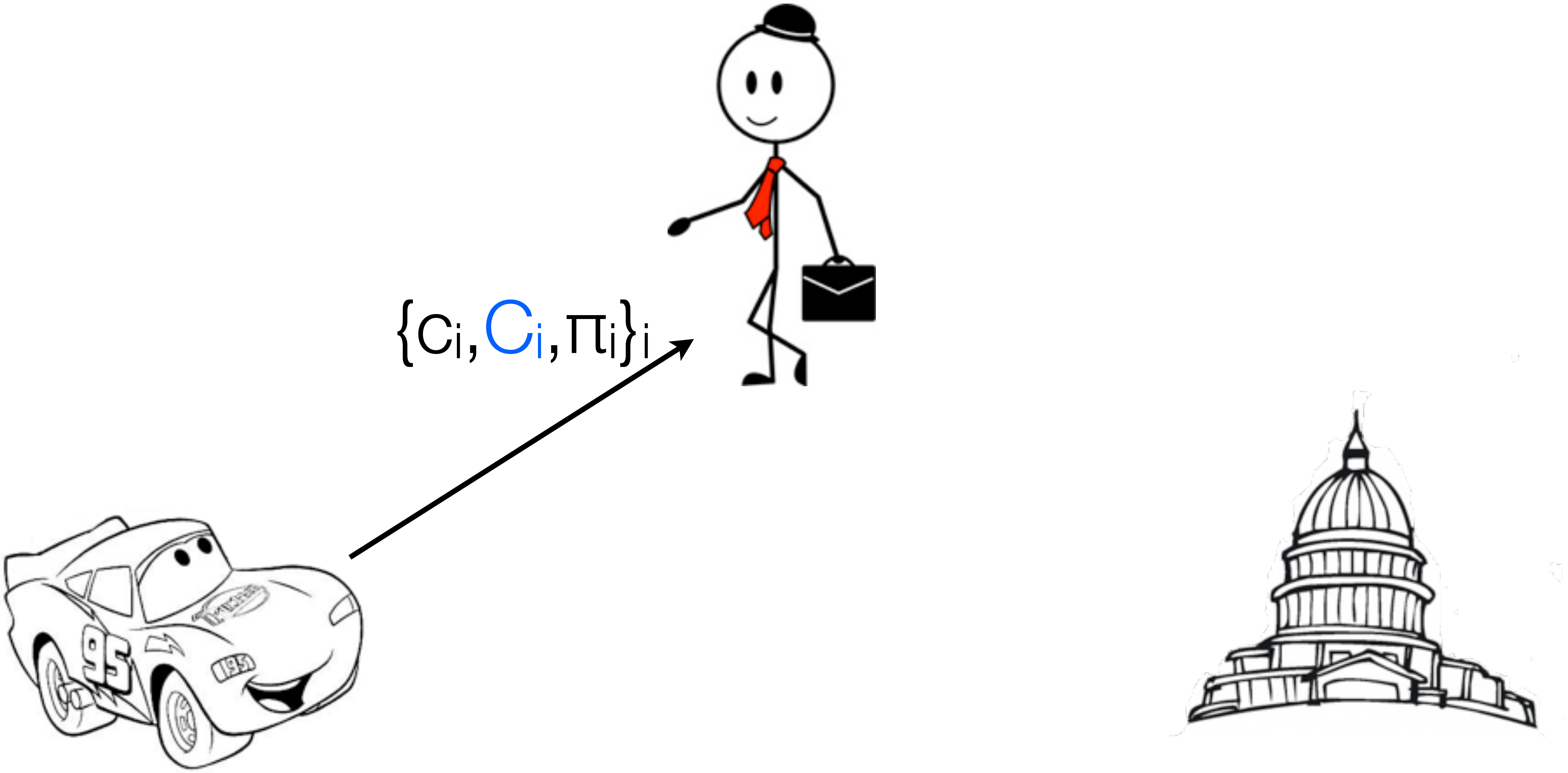

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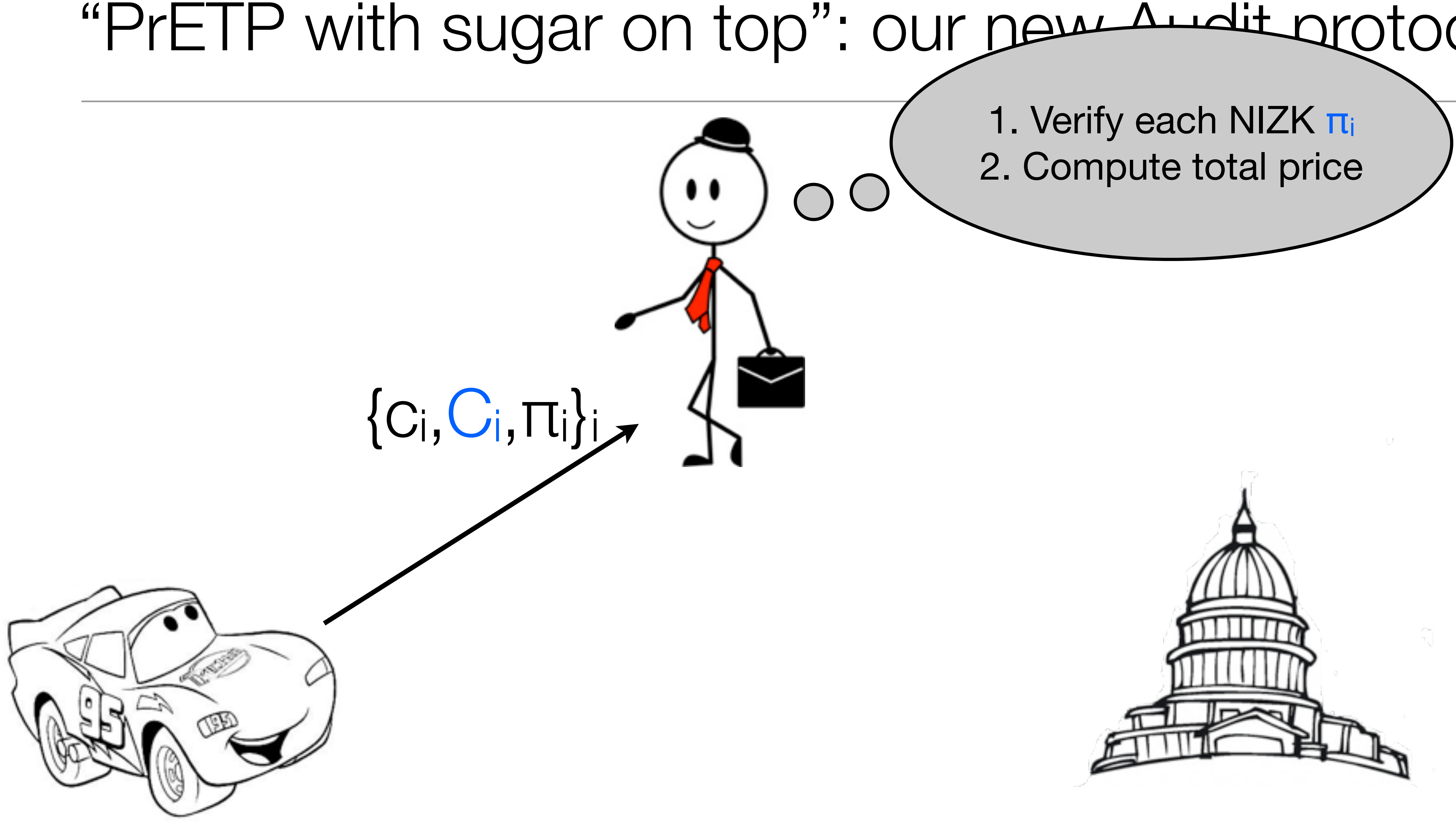

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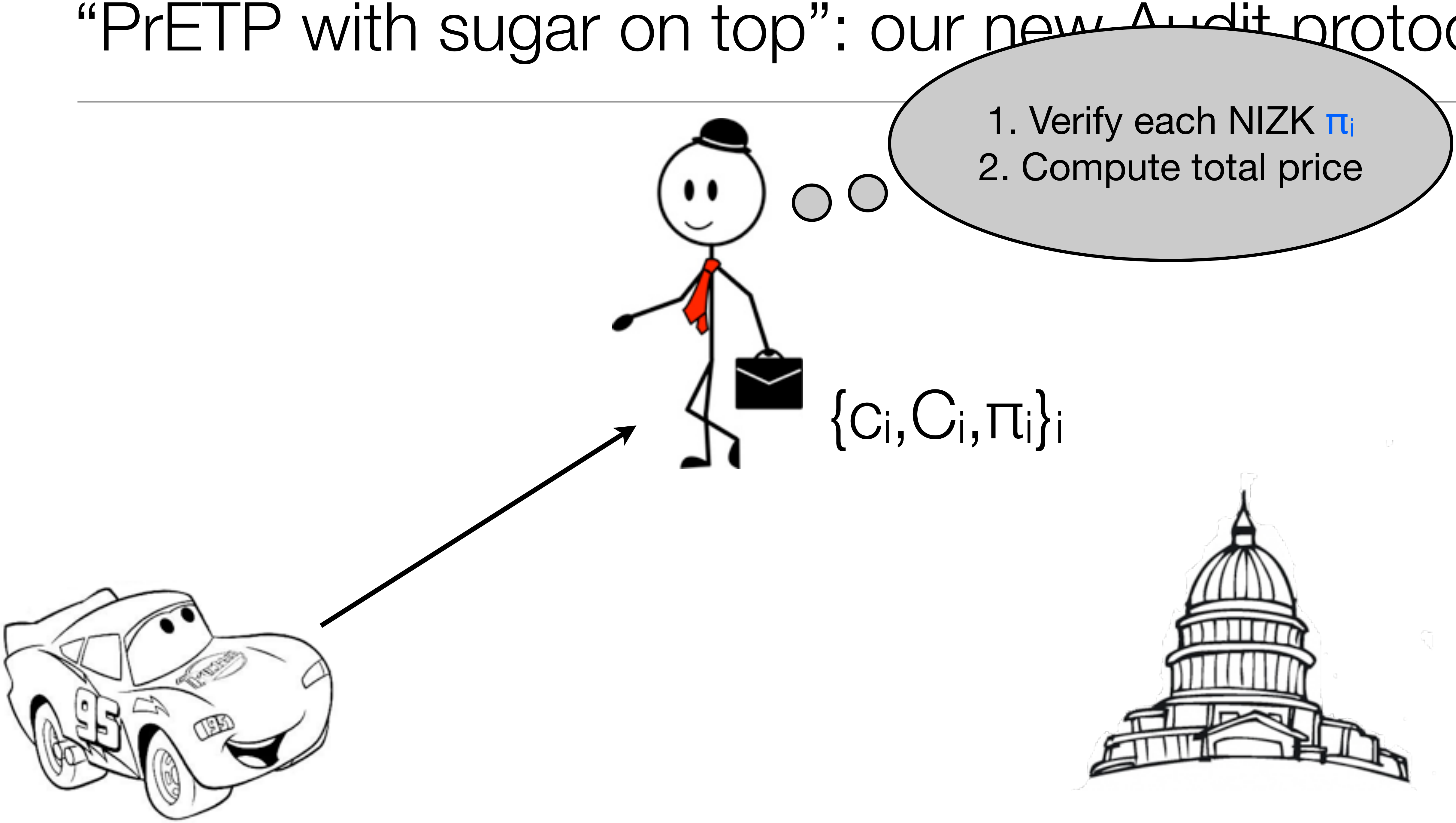

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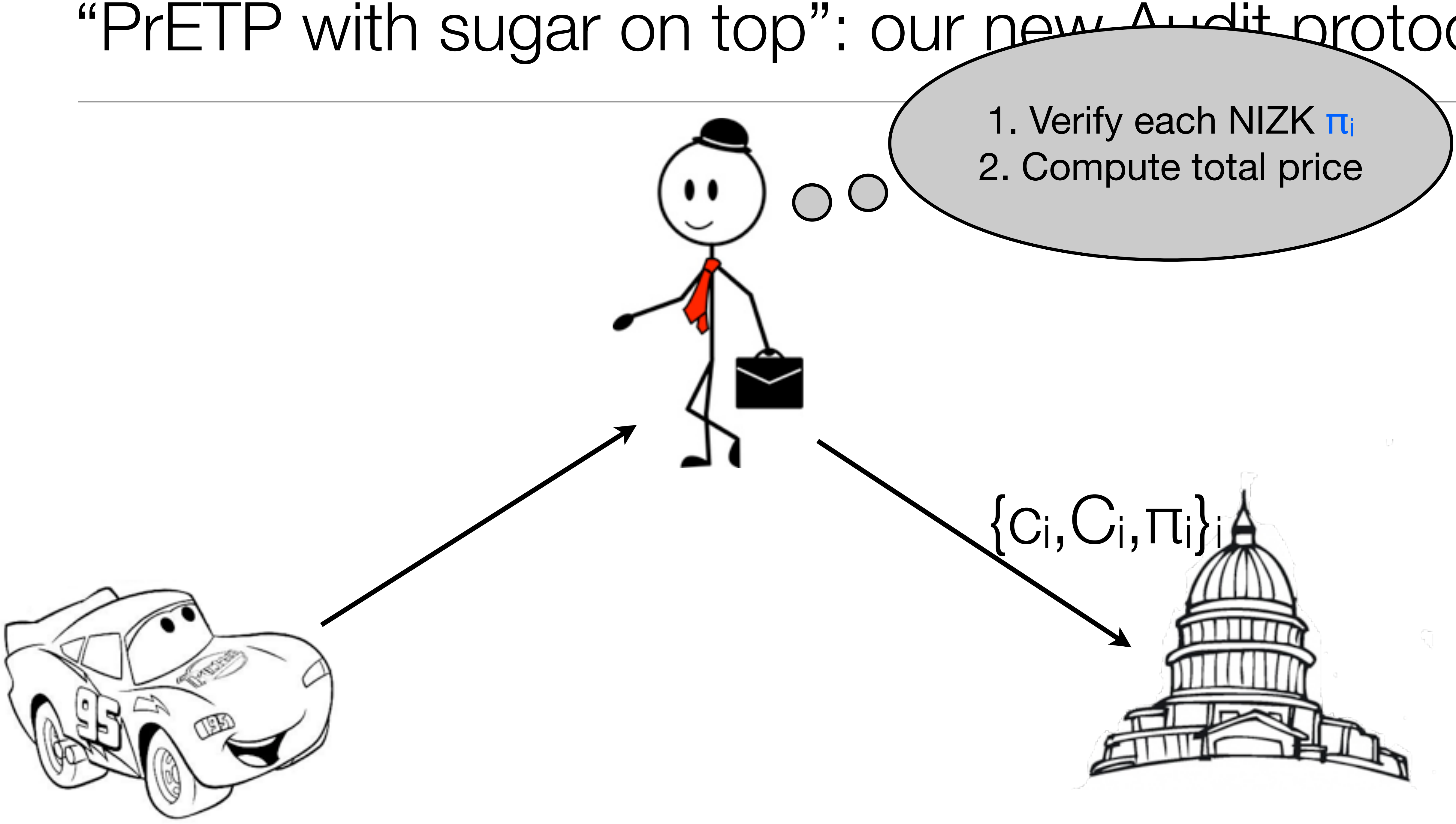

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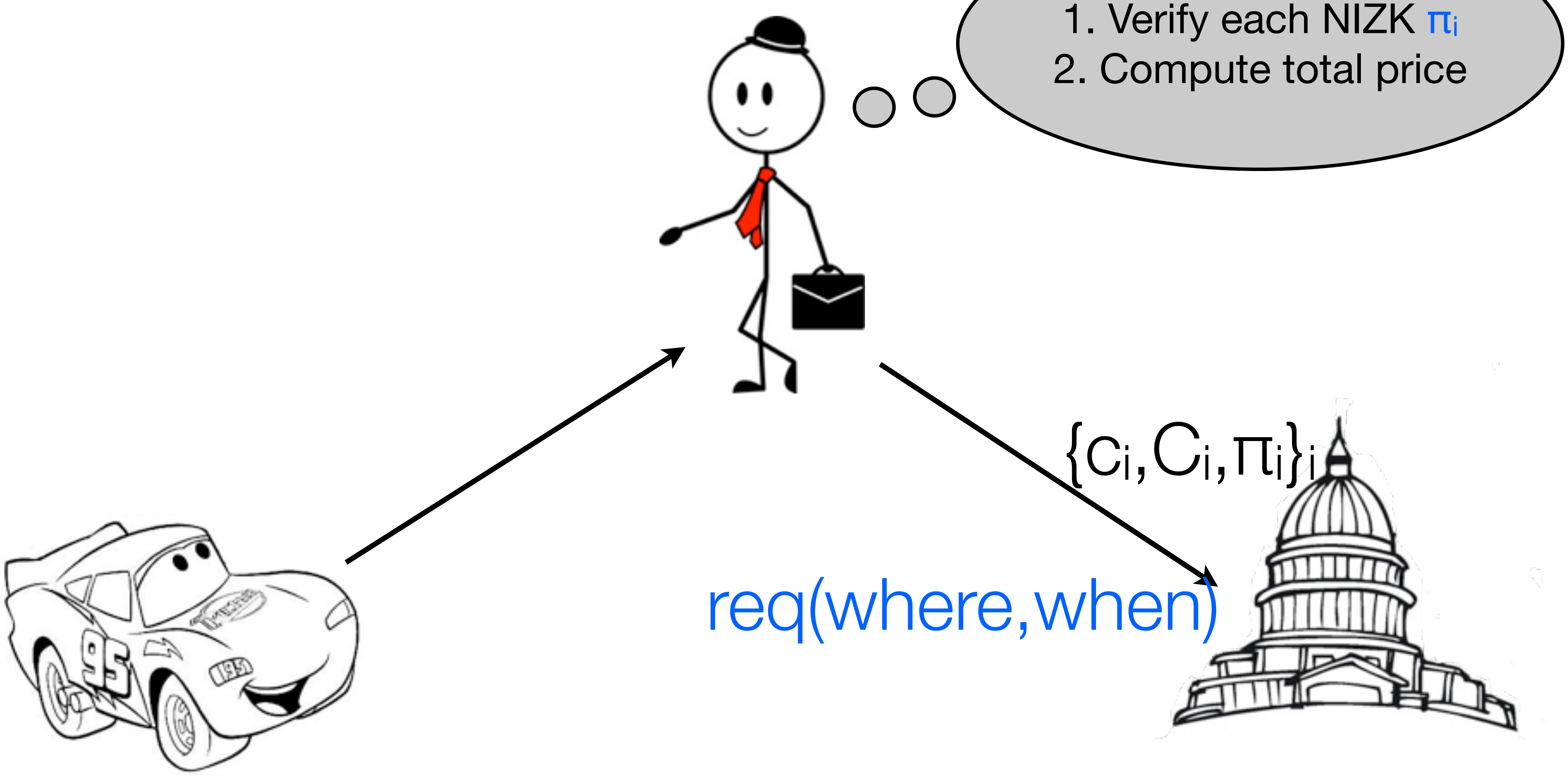

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req(where,when)

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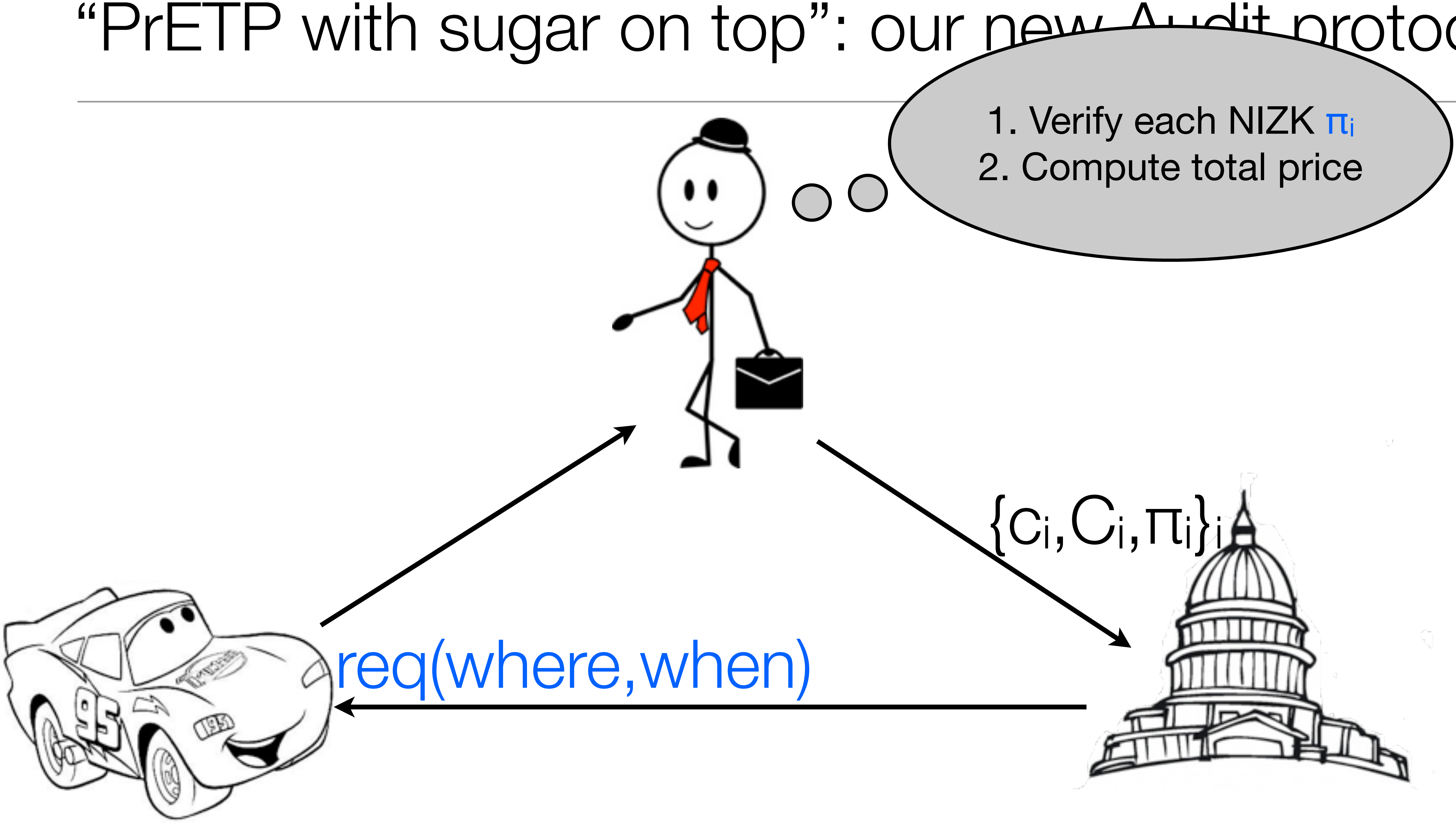

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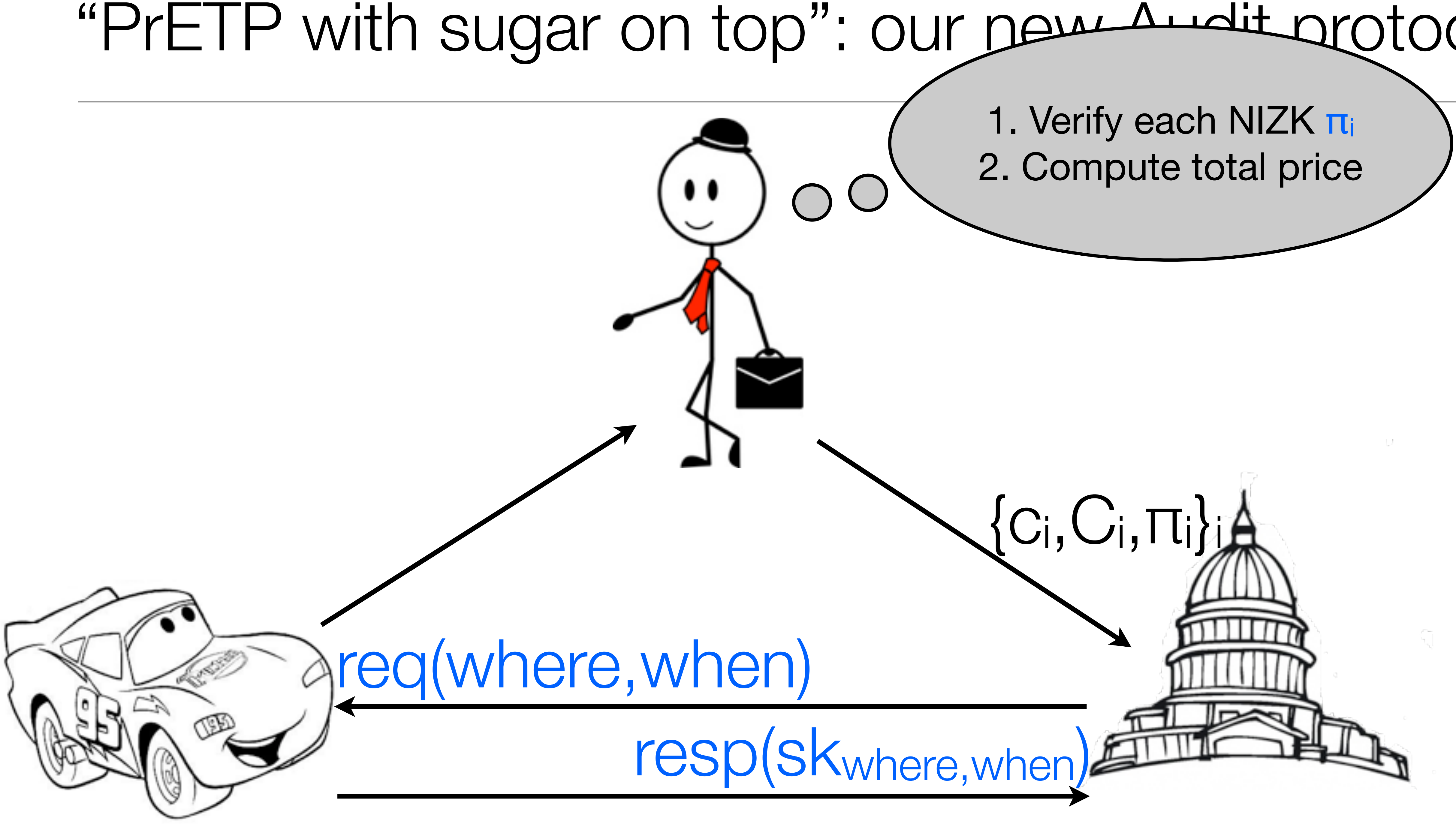

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$\{c_i, C_i, \pi_i\}_i$

req(where,when)

resp($sk_{where,when}$)

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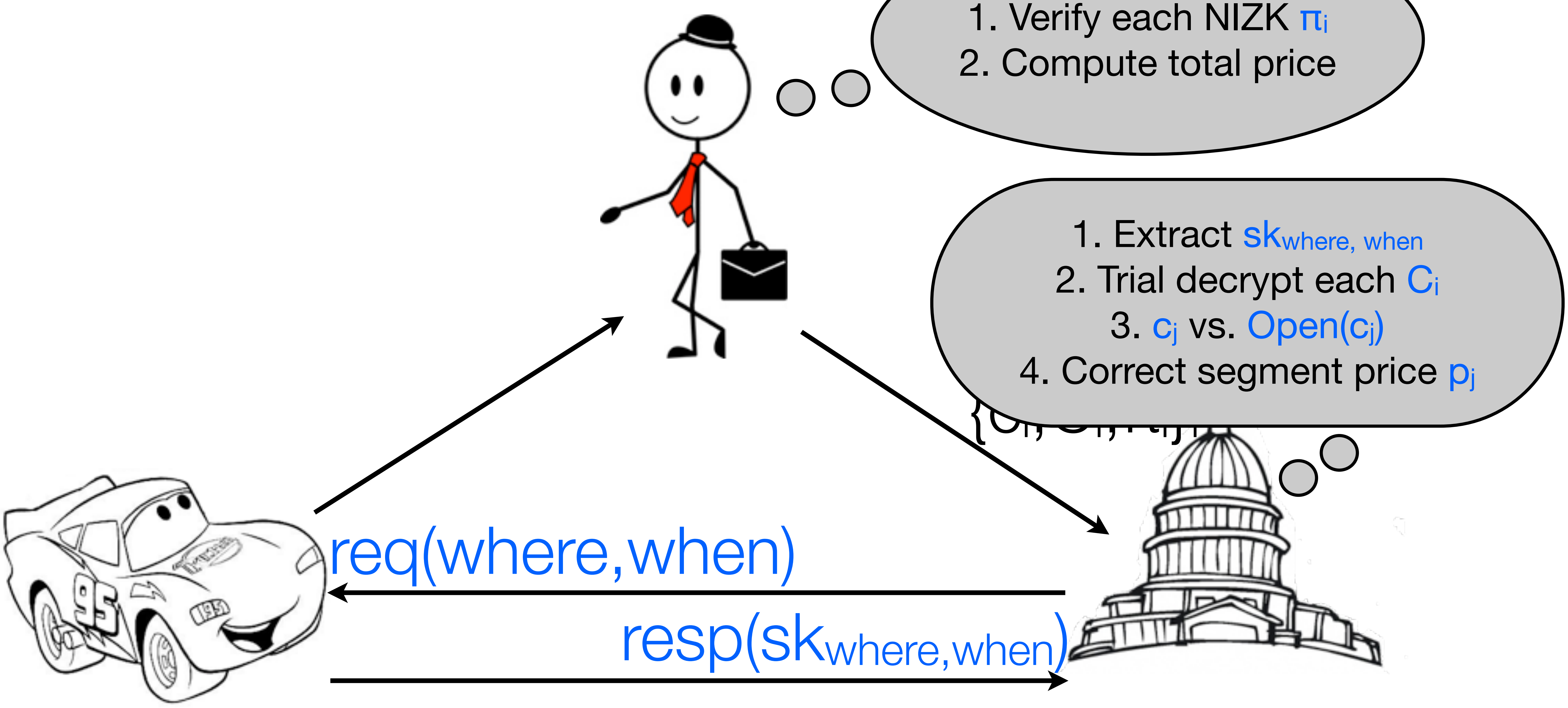

1. Verify each NIZK π_i
2. Compute total price

1. Extract $sk_{where, when}$
2. Trial decrypt each C_i
3. c_j vs. Open(c_j)
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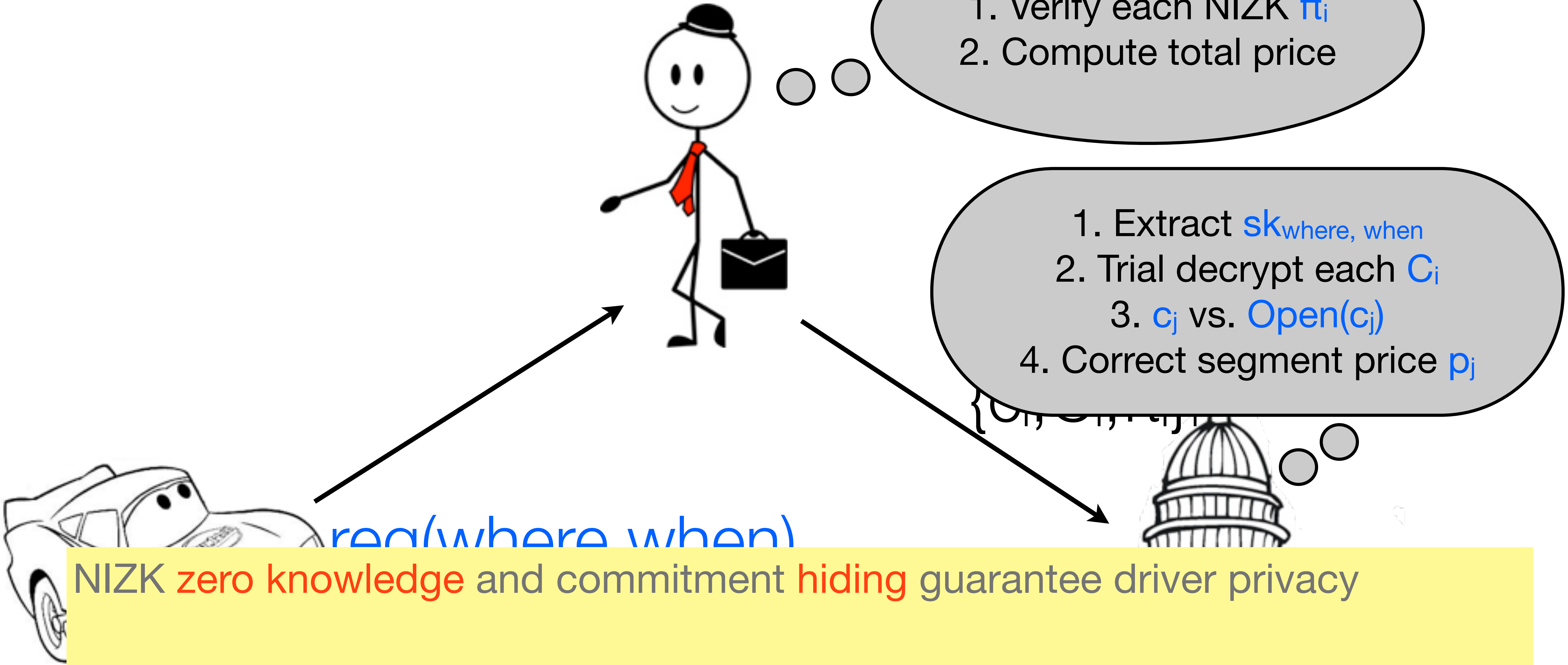

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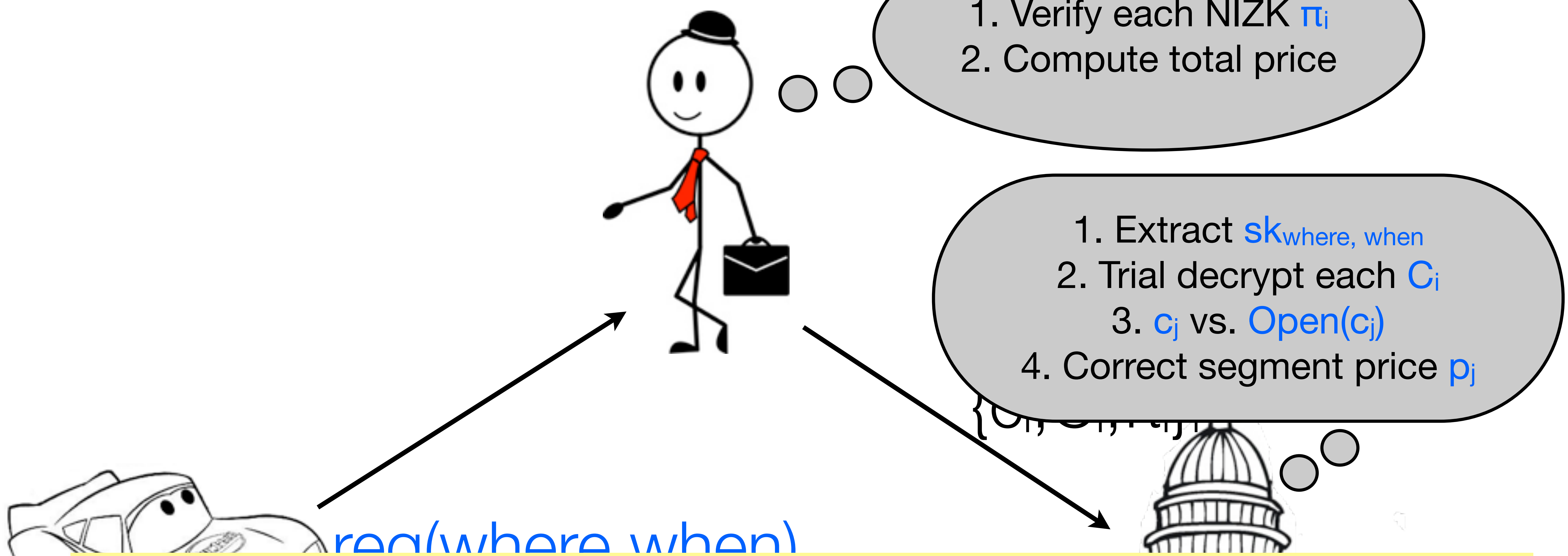

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Commitment binding guarantees c_j is the right commitment for (where,when)

IBE blindness guarantees that driver doesn’t learn segment (where,when)

Outline

Cryptographic background

Milo

Evaluation

Implementation details

Milo’s performance

Conclusions

Implementation

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Used MIRACL [Scott] for blind IBE, ZKPDL [MEKHL’10] for commitments and NIZKs

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When are blind IBE operations happening?

Implementation

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When are blind IBE operations happening?

- Encryption: during Payment process
- Extraction: during Audit (OBU as authority, TC as user)
- Decryption: during Audit (TC needs to trial decrypt each ciphertext)

Various measurements: time and space

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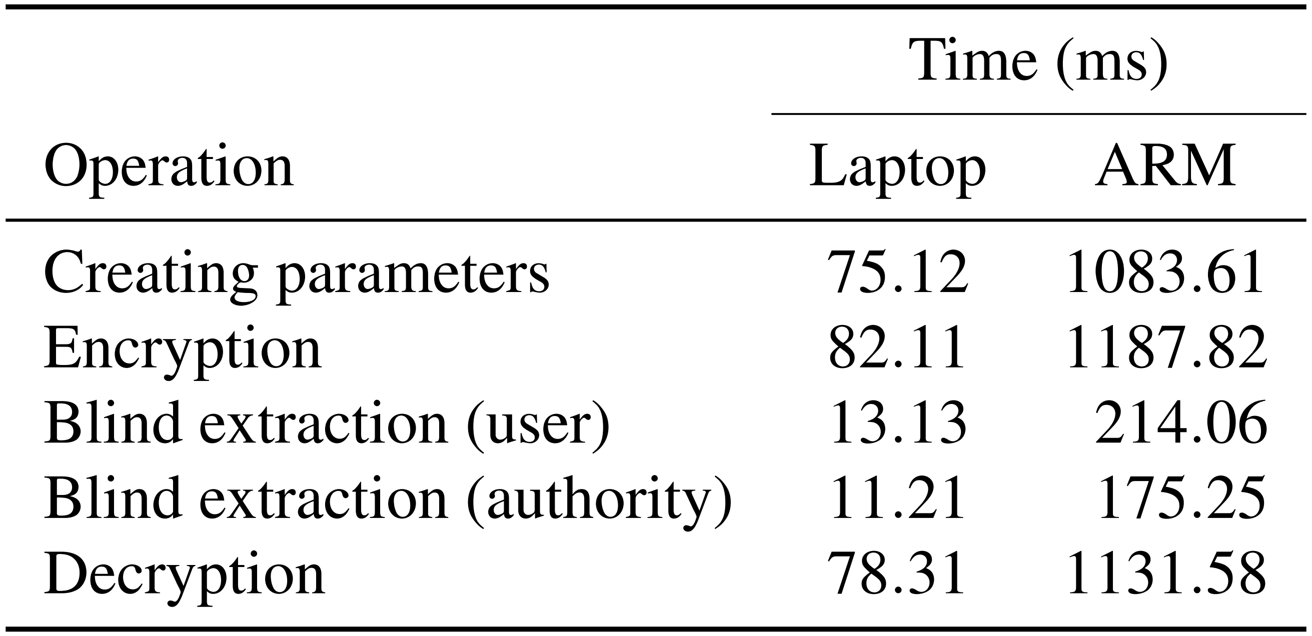
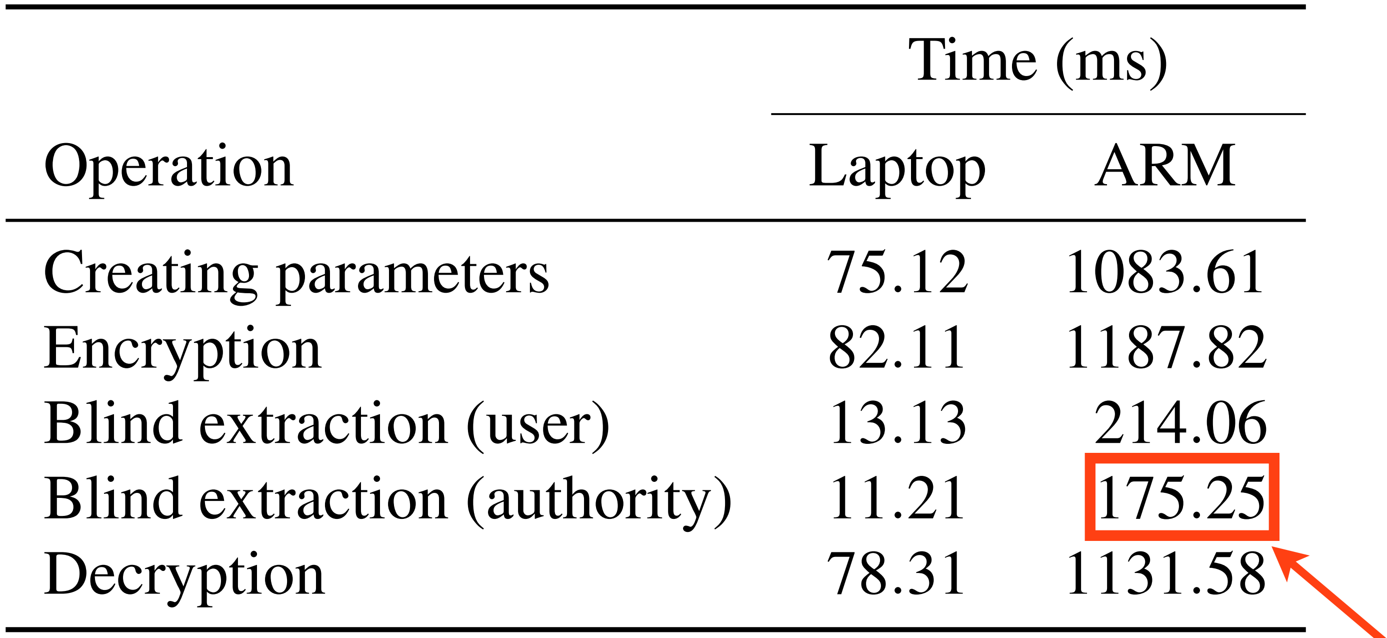


	Time (ms)	
Operation	Laptop	ARM
Creating parameters	75.12	1083.61
Encryption	82.11	1187.82
Blind extraction (user)	13.13	214.06
Blind extraction (authority)	11.21	175.25
Decryption	78.31	1131.58

Time for blind IBE

Various measurements: time and space



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Time for blind IBE

cost for OBU during
Audit is reduced

Various measurements: time and space

	Time (ms)	
Operation	Laptop	ARM
Creating parameters	75.12	1083.61
Encryption	82.11	1187.82
Blind extraction (user)	13.13	214.06
Blind extraction (authority)	11.21	$\boxed{175.25}$
Decryption	78.31	1131.58

Time for blind IBE

Object	Size (B)
NIZK	5455
Commitment	130
Ciphertext	366
Total Pay segment	5955
Audit message	494

Size for messages

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Time for TC to perform Audit

Length	Time step	Segments	Time for TC (s)
1 mile	1 minute	2000	55.68
1 mile	1 hour	1000	33.51
2 miles	1 hour	500	10.45

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Outline

Cryptographic background

Milo

Evaluation

Conclusions

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- Found that computational overhead was manageable, significantly cheaper than certain alternatives

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Thanks!
Any questions?

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