Linux-Stack Based V2X Framework: All You Need to Hack Connected Vehicles

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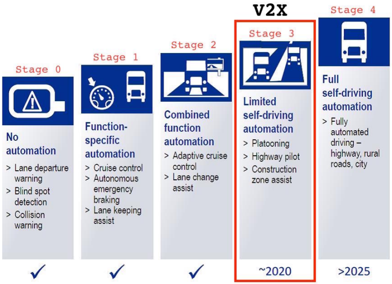
State of the World: (Semi)Autonomous Driving Technologies

- Vehicular automation widespread in global industry
- Automated driving technologies becoming accessible to general public

- Comms protocols used today in vehicular networks heavily flawed
- New automated technologies still using CANBUS and derivatives

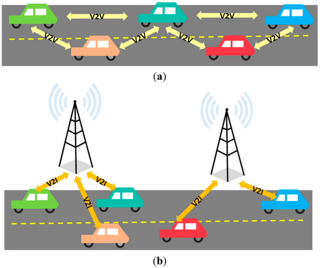
Stages of Autonomy

- Today: Stage 2 Autonomy - Combined Function Automation


V2X
Stage 0
No automation
> Lane departure warning
> Blind spot detection
> Collision warning
✓
Stage 1
Function-specific automation
> Cruise control
> Autonomous emergency braking
> Lane keeping assist
✓
Stage 2
Combined function automation
> Adaptive cruise control
> Lane change assist
✓
Stage 3
Limited self-driving automation
> Platooning
> Highway pilot
> Construction zone assist
~2020
Stage 4
Full self-driving automation
> Fully automated driving – highway, rural roads, city
>2025

- V2X: Stage 3 Autonomy - Combined Function Automation
  ⇒ Leverage vehicular ad hoc mesh network for exchange of safety and actor/world state information

Critical Aspects of V2X



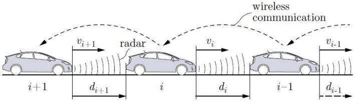
(a)

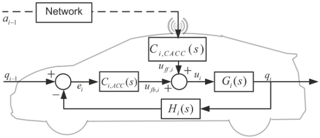
(b)

- Reliable high-throughput ad hoc mesh networking and exchange in a real-time cyberphysical environment
- Standardization of Stage 3 automation in federal and consumer transportation systems
- Enhanced safety and traffic optimization technologies leveraging V2X

Technologies Using V2X

- Collision avoidance (Forward Collision Warning) systems
- Advanced Driver Assistance Systems (ADAS)





- Cooperative adaptive cruise control
- Automated ticketing and tolling

Impact of V2X: Why Care?

- Most importantly: self-driving cars are shiny

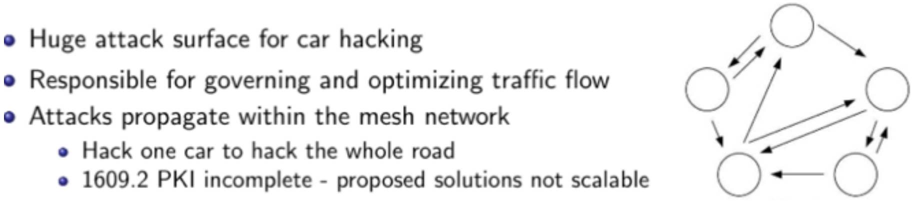
- Your children will (would) ride in these
- Enables safety functions not possible with onboard systems
- V2X technologies applicable across range of cyberphysical systems
- NHTSA V2V NPRM: V2V to be standardized in light vehicles
- It‘s happening: You want in?

Tangible Benefits

According to the USDOT,

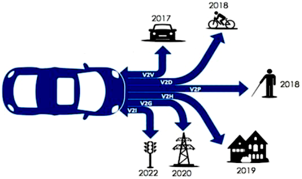
- Safety
  - Prevent 25,000 to 592,000 crashes annually
  - Save 49 to 1,083 lives
  - Avoid 11,000 to 270,000 injuries
  - Prevent 31,000 to 728,000 property damaging crashes
- Travel time
  - 27% reduction for freight
  - 23% reduction for emergency vehicles
  - 42% reduction on freeway (with cooperative adaptive cruise control & speed harmonization)

Impact on Automotive Security



- Huge attack surface for car hacking
- Responsible for governing and optimizing traffic flow
- Attacks propagate within the mesh network
  - Hack one car to hack the whole road
  - 1609.2 PKI incomplete - proposed solutions not scalable

- Will drive adoption and development of autonomous vehicles
- Homogeneous use of WAVE and V2X enables unprecedented complexity in transportation systems



V2X Protocol Stack

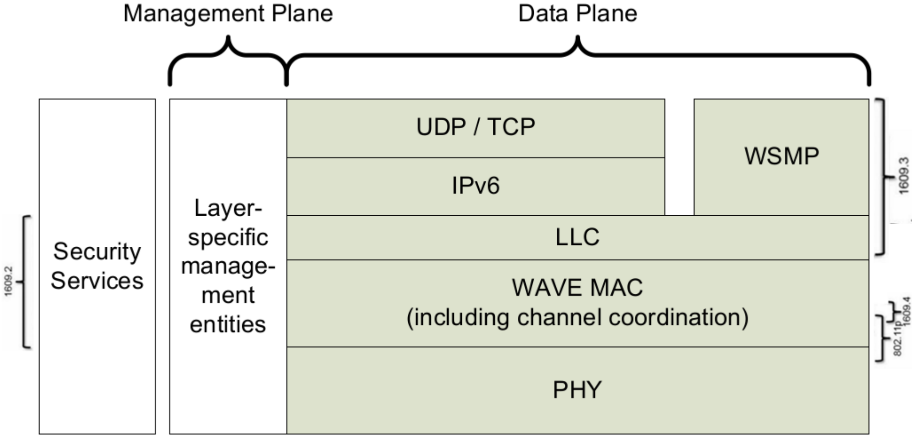
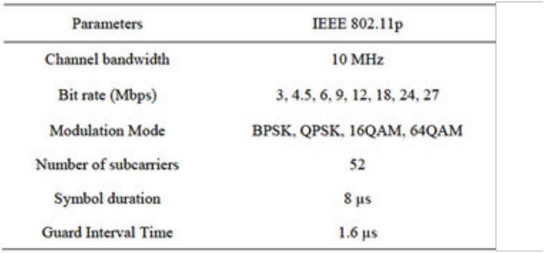


Figure 1—WAVE reference model

IEEE 802.11p

Wireless Access in Vehicular Environments

- Amendment to IEEE 802.11-2012 to support WAVE/DSRC
- PHY layer of V2X stack
- No association, no authentication, Wildcard BSSID = {ff:ff:ff:ff:ff:ff}
- 5.8-5.9GHz OFDM



Parameters	IEEE 802.11p
Channel bandwidth	10 MHz
Bit rate (Mbps)	3, 4.5, 6, 9, 12, 18, 24, 27
Modulation Mode	BPSK, QPSK, 16QAM, 64QAM
Number of subcarriers	52
Symbol duration	8 µs
Guard Interval Time	1.6 µs

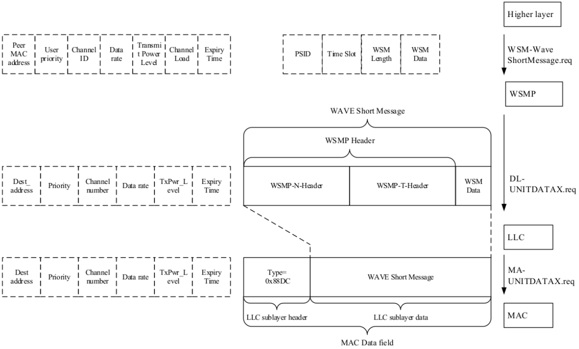
IEEE 1609

WAVE Short Message Protocol (WSMP)

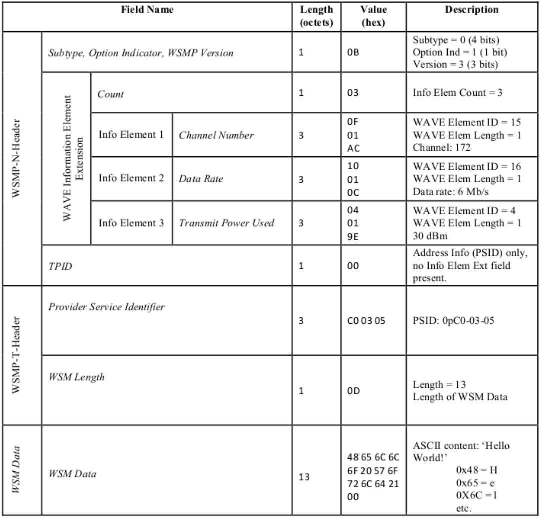
- 1609.2 Security Services
  - PKI, cert revocation, misbehavior reporting
- 1609.3 Networking Services
  - Advertisements, message fields
- 1609.4 Multi-Channel Operation
  - Channel sync, MLMEX
- 1609.12 Identifier Allocations
  - Provider service IDs

IEEE 1609.3: WSM

Packets encoded as WAVE Short Messages (WSMs)



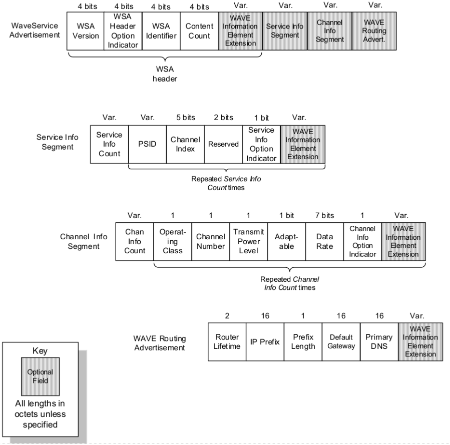
IEEE 1609.3: WSM Example



Field Name				Length (octets)	Value (hex)	Description
WSMP-N-Header	*Subtype, Option Indicator, WSMP Version*			1	0B	Subtype = 0 (4 bits) Option Ind = 1 (1 bit) Version = 3 (3 bits)
	WAVE Information Element Extension	*Count*		1	03	Info Elem Count = 3
		Info Element 1	*Channel Number*	3	0F 01 AC	WAVE Element ID = 15 WAVE Elem Length = 1 Channel: 172
		Info Element 2	*Data Rate*	3	10 01 0C	WAVE Element ID = 16 WAVE Elem Length = 1 Data rate: 6 Mb/s
		Info Element 3	*Transmit Power Used*	3	04 01 9E	WAVE Element ID = 4 WAVE Elem Length = 1 30 dBm
	TPID			1	00	Address Info (PSID) only, no Info Elem Ext field present.
WSMP-T-Header	*Provider Service Identifier*			3	C0 03 05	PSID: 0pC0-03-05
	WSM Length			1	0D	Length = 13 Length of WSM Data
WSM Data	*WSM Data*			13	48 65 6C 6C 6F 20 57 6F 72 6C 64 21 00	ASCII content: 'Hello World!' 0x48 = H 0x65 = e 0X6C = l etc.

IEEE 1609.3: WSA

Participants broadcast WAVE Service Advertisements (WSAs)



	4 bits	4 bits	4 bits	4 bits	Var.	Var.	Var.	Var.
WaveService Advertisement	WSA Version	WSA Header Option Indicator	WSA Identifier	Content Count	WAVE Information Element Extension	Service Info Segment	Channel Info Segment	WAVE Routing Advert.

WSA header

	Var.	Var.	5 bits	2 bits	1 bit	Var.
Service Info Segment	Service Info Count	PSID	Channel Index	Reserved	Service Info Option Indicator	WAVE Information Element Extension

Repeated *Service Info Count* times

	Var.	1	1	1	1 bit	7 bits	1	Var.
Channel Info Segment	Chan Info Count	Operat-ing Class	Channel Number	Transmit Power Level	Adapt-able	Data Rate	Channel Info Option Indicator	WAVE Information Element Extension

Repeated *Channel Info Count* times

	2	16	1	16	16	Var.
WAVE Routing Advertisement	Router Lifetime	IP Prefix	Prefix Length	Default Gateway	Primary DNS	WAVE Information Element Extension

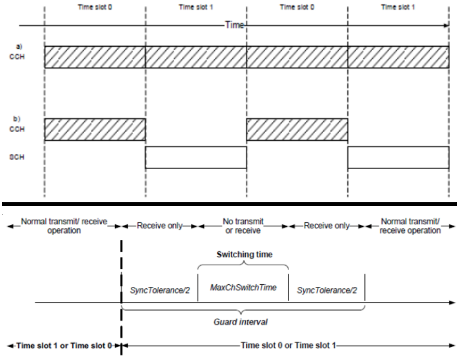
Key

▨ Optional Field

All lengths in octets unless specified

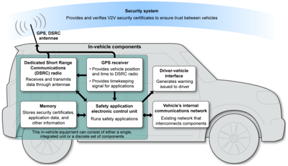
IEEE 1609.4: Channel Synchronization

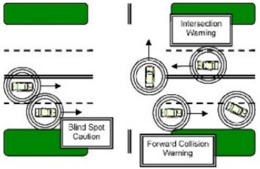
Control and service channels (CCH and SCH)



SAE J2735

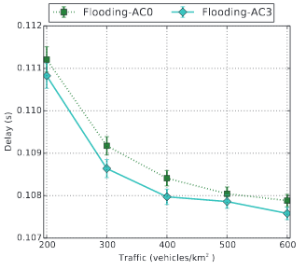
- DSRC message set and data elements
- ASN1 UPER encoding (latest rev does not compile)
- Basic Safety Message (BSM), Emergency Vehicle Alert (EVA), etc.


Security system
Provides and verifies V2V security certificates to ensure trust between vehicles
GPS, DSRC antennae
In-vehicle components
Dedicated Short Range Communications (DSRC) radio
Receives and transmits data through antennae
GPS receiver
• Provides vehicle position and time to DSRC radio
• Provides timekeeping signal for applications
Driver-vehicle interface
Generates warning issued to driver
Memory
Stores security certificates, application data, and other information
Safety application electronic control unit
Runs safety applications
Vehicle's internal communications network
Existing network that interconnects components
This in-vehicle equipment can consist of either a single, integrated unit or a discrete set of components



Subtleties in Protocol Specifications

- Ambiguous parse rules for certain frames (Information Element Extension)
- Services are gated only by PKI permissions
  - Proprietary applications using ad hoc permissions
- Messages leak S/PII
  - Misbehavior reporting just randomizes the send address in an attempt at privacy
  - WSA fingerprinting prevents privacy
- Channel switching for single-antenna systems desync
  - $>$0.1s delay with 200 cars/km^2



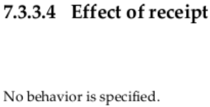
State of V2X Standards

- IEEE 802.11-2012 details 802.11p
  - Not supported by majority of COTS WiFi hardware
- IEEE 1609.{3,4} stable, under development
- IEEE 1609.2 (PKI, misbehavior reporting) incomplete, under development
- SAE J2735 stable, under development
  - SAE J2735 ASN1 (2016) not stable
  - Example of PKI Brilliance: *'Another aspect of the privacy and non-tracking of vehicles becomes apparent here as the MAC address needs to be randomly changed to prevent vehicle tracking.'*

Possibly Unintentional Obfuscation of the Standards

- Removal of message CRC from J2735
- Continued revisions would likely make in-the-field devices obsolete
  - WSMPv3 (current) has no backwards compatibility
- Standards vague in best practices, favoring proprietary implementations

Consider:



7.3.3.4 Effect of receipt

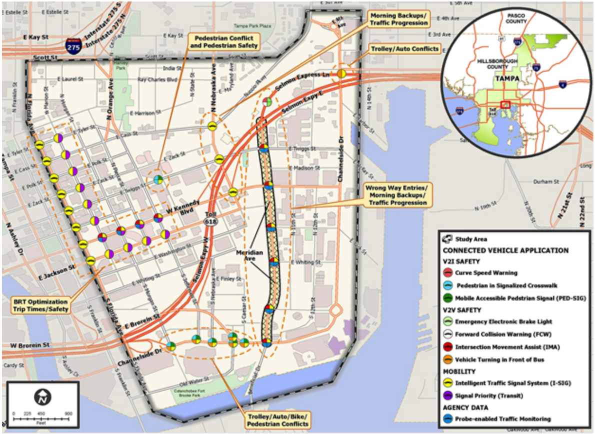
No behavior is specified.

Major Changes to the Standards

- Standards still in development after decades
  - Spectrum allocated by the FCC in 1999
  - WAVE first codified in 2005
  - J2735 in 2006
- Rewrites of security services to change certificate structure
- Rewrites of management plane to add services (P2PCD)
- Incomplete safety message dictionary
- No standards for application-layer services

Physical Manifestations of V2X: Deployment

Three USDOT pilot studies: NYC, Tampa (THEA), Wyoming


Morning Backups/ Traffic Progression
Pedestrian Conflict and Pedestrian Safety
Trolley/Auto Conflicts
Wrong Way Entries/ Morning Backups/ Traffic Progression
BRT Optimization Trip Times/Safety
Trolley/Auto/Bike/ Pedestrian Conflicts
Meridian Ave
PASCO COUNTY
HILLSBOROUGH COUNTY
TAMPA
Study Area
CONNECTED VEHICLE APPLICATION
V2I SAFETY
Curve Speed Warning
Pedestrian in Signalized Crosswalk
Mobile Accessible Pedestrian Signal (PED-SIG)
V2V SAFETY
Emergency Electronic Brake Light
Forward Collision Warning (FCW)
Intersection Movement Assist (IMA)
Vehicle Turning in Front of Bus
MOBILITY
Intelligent Traffic Signal System (I-SIG)
Signal Priority (Transit)
AGENCY DATA
Probe-enabled Traffic Monitoring
W Kennedy Blvd
Selmon Expy
Selmon Express Ln
Channelside Dr
E Brorein St
W Brorein St
E Jackson St
N Florida Ave
N Nebraska Ave
N Orange Ave
Scott St
E Kay St
Interstate 275

V2X in the Linux Networking Subsystem

802.11p: Driver and Kernel Tree Modifications

- WiFi driver modifications:
  - Add support for ITS-G5 channel spectrum, 5/10MHz-width channels
  - Add support and error checking for OCB mode
  - Force usage of user-specified regulatory domain
- /net/wireless modifications:
  - Add support wildcard broadcast transmission
  - Add support for 5/10MHz-width channels, channel state definitions for OCB mode
  - Force usage of user-specified regulatory domain
- mac80211 modifications:
  - Add (fix) support and error checking for OCB mode
    - Initialization and de-initialization
    - Channel filter configuration, disable beaconing and association
- cfg80211 modifications:
  - Channel filter configuration for OCB mode
  - Add support for 5/10MHz-width channels
- nl80211 modifications:
  - Channel filter configuration for OCB mode
  - Add support for 5/10MHz-width channels

IEEE 1609: 1609 in the Linux Kernel

Kernel module to pack, parse, and broadcast messages

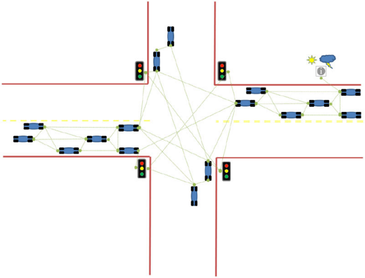
- Relevant data structures
  - WSM, WSA, WRA, SII, CII, IEX
- Full control of fields
  - subtype, TPID, PSID, chan, tx power, data rate, location, etc.
  - Operating modes for setting degree of compliance to standard (strict, lax, loose)
- Channel sync, dispatch
- Netlink socket interface to userspace (`af_wsmp`)

Error Checking and Corrections Implemented

- Parser short circuiting
- Domain checks on each field
- Operating modes for standard compliance
    - Will reject messages where domain is non-compliant
- Relevant error handling (EBADMSG, EINVAL, EFAULT, etc.)

SAE J2735: Userspace J2735 Message Dictionary

- socketv2v utility suite: v2vsend, v2vdump, v2vsniffer
- Fully implements BSM, EVA, RSA, CSR J2735 message formats
- Communicates with 1609 kernel module via Netlink socket
- Enables VANET participation with generic Linux box and 5GHz WiFi



Platform Requirements: Linux!

- V2X stack integrated in mainline Linux kernel
    - No proprietary DSRC hardware/software required
    - V2X stack current - deployed V2X ‘solutions’ obsolete
- Currently supports ath9k/ath9k_htc, rtlwifi
- Fully implements 802.11p, IEEE 1609.{3,4} in Linux networking subsystem
- IEEE 1609.2 to be integrated upon completion

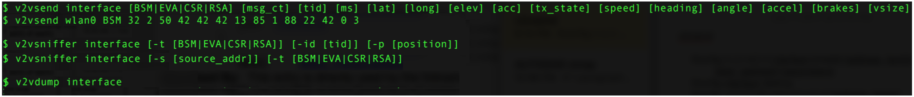
Capabilities Leveraging V2X Stack: Hacking Connected Vehicles

- Rapidly prototype new V2V applications
- Penetrate commercial implementations
- Analyze real V2V network data
    - Pilot studies, protocol analysis

Developing Connected Vehicle Technologies

- Widespread access enables engagement of security (1337) community in standards development
  - History lesson: CANBUS sucks (for automotive)
- Interact with existing V2X infrastructure
  - Pressure manufacturers and OEMs to implement functional V2V
- Deploy ahead of market - experimental platforms
  - UAS, maritime, orbital, heavy vehicles
- Opportunity for empirical research: See what you can break
  - Straightforward to wardrive
  - Hook DIY radio (Pi Zero with 5GHz USB adapter) into CANBUS (for science ONLY)

(You can) Use J2735 DSRC over 802.11p with Linux



```
$ v2vsend interface [BSM|EVA|CSR|RSA] [msg_ct] [tid] [ms] [lat] [long] [elev] [acc] [tx_state] [speed] [heading] [angle] [accel] [brakes] [vsize]
$ v2vsend wlan0 BSM 32 2 50 42 42 42 13 85 1 88 22 42 0 3

$ v2vsniffer interface [-t [BSM|EVA|CSR|RSA]] [-id [tid]] [-p [position]]
$ v2vsniffer interface [-s [source_addr]] [-t [BSM|EVA|CSR|RSA]]

$ v2vdump interface
```

- Participate in connected VANETS
  - v2vsend: Craft and inject messages into ITS spectrum
  - v2vsniffer: Sniff particular messages from specific actors
  - v2vdump: Sniff all communications on ITS channels

DSRC Sniffing/Wardriving

- DSRC is a broadcast protocol
- Dimensions, directionality, orientation, acceleration, display etc. provide means to easily fingerprint and track participants
- From the SAE DSRC Implementation Guide:
  - *'The VII Probe Data Service collects anonymous probe data from all Mobile Users, and distributes it to any authorized Network User or Roadside Infrastructure User that requests it.'*
  - *'Applications are initialized by matching the locally registered AID with an advertised AID (application announcement) received on the radio link'*
- Highly distributed infrastructure - attacks propagate across the network easily

Understanding the Adversary

- Passive
  - Determine trajectory of cars within some radius
    - Few stations required to monitor a typical highway
  - Determine services provided by peers
  - Characterize network traffic for regions of the road
  - Uniquely fingerprint hardware being used
    - RF signature
    - Probe responses
- Active
  - Deny service
  - Manipulate misbehavior reports
  - Exploit bad hardware/software to access CANBUS
    - Different regional configurations can lead to undefined behavior
  - Disrupt vehicle traffic
  - Parade as a moving toll station
    - Ad hoc PKI for application-layer services

Hacking ITS

- Level 1: Denial of Service
  - Single-antenna DSRC systems susceptible to collision attack
- Level 2: DSRC spectrum sweep, enumerate proprietary (custom) services available per participant
- Level 3: Impersonate an emergency vehicle
- Level 4: Become mobile tollbooth
- Level 1337: Remotely execute platooning service
  - Assume direct control

Protocol Exploitation

Use design flaws in the VANET to create rapidly propagating effects

- Privacy mitigations put in as an afterthought
- PKI/trust management doesn't scale
- XML-driven J2735 safety message dictionary
- Any RSU deployed is a single point of failure for the region

Global Access to V2X

- Provides vehicle to streamline testing and development of V2X
- Mainline Linux kernel integration ≡ V2X stack easily applied to UAS, maritime, heavy truck, communications systems, etc.
- V2X now tangible, scalable, accessible: Now it is up to us to fix it!

What: V2X in Your Hands

- Shape the future development of ITS
  - Fix/mitigate systemic issues in VANET security
- Push toward free as in freedom solutions
- Reduce global attack surface through engineering of good standards

- Engage and participate in public VANET (hack the planet)

Acknowledgments

References

- Check me out on github: https://github.com/p3n3troot0r/Mainline-80211P

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