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The multi-facets of building dependable applications over connected physical objects

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Due to my own research background, I will address the topic from the perspective of software engineering, and draw examples from RFID applications for illustration.

Yet, the concepts and issues discussed should be generalizable to the physical objects connected using other wireless technologies, such as wifi, zigbee, bluetooth and so on.

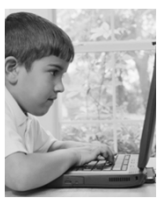
Many interesting issues arise from connected physical objects (CPO). I may not have answers to most of the issues. **BUT**, I will share with you our past experience.

A story from Mr. Bean …

Jerry Bean's diary

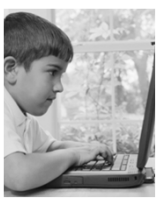
Who is Jerry Bean?

- Jerry is completing his first year of PhD study.
- He understands that PhD study requires a clear mission.
  - Buy house and get married soon after graduation.
- He decides to work on a topic with promising research and business opportunities.
- He has an adviser working on software engineering.



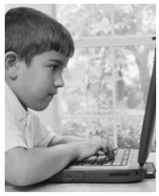
Who is Jerry Bean (cont.)?

Most importantly, his adviser wants him to publish at ICSE, ESEC-FSE, FASE, ISSTA, …



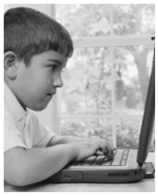
What are connected physical objects (CPO)?

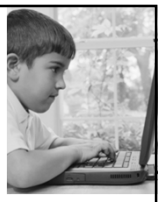
Jerry's story (Part I)



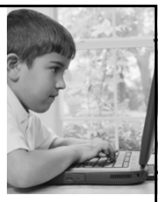
What are connected physical objects?

- Jerry loves YouTube.
- One day, he found a video.

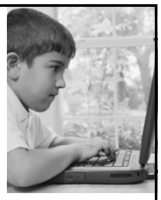




Jerry gets interested and looks further into RFID …



INTERESTING!!
Connected physical objects are shaping our behaviors in every walk of life.



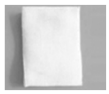
They also help us to meet new standards and guidelines

WHO Guidelines for Safe Surgery 2009

- Objective 7: The team will prevent inadvertent retention of instruments or sponges in surgical wounds.
  - Need to systematically track/count the sponges used in an operation.

RFID-enabled sponges

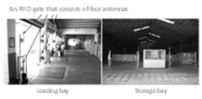
- Real-time tracking and counting sponges used in an operation



RFID-enabled sponge

Connected physical objects (CPO)

- Stay connected.
  - Multiple networking technologies: Wifi, Zigbee, Bluetooth, RFID, …



- Identify themselves actively.
- Feature tight combination of computational and physical elements.
- Tight integration of computation and physical processes.

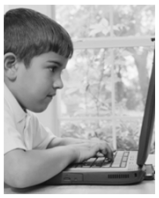
Connected physical objects (CPO)

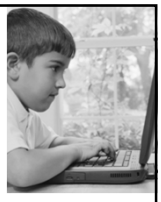
Call for interdisciplinary efforts:

- Algorithm
- Database
- Pervasive computing
- Logistics management
- …
- **Software engineering**

Where are the software engineering research problems?

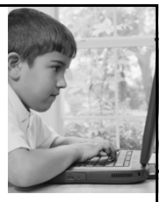
Jerry's story (Part II)





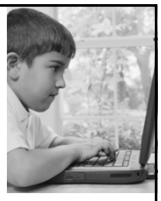
Question

Are there any fundamental differences between CPO systems and conventional software systems?



Question

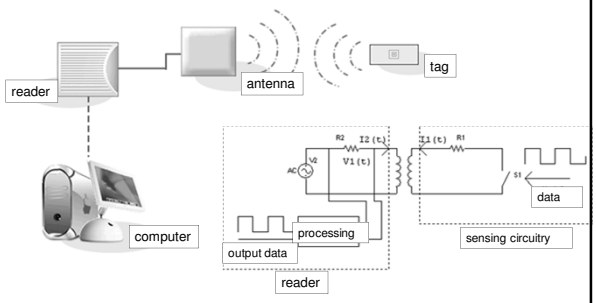
In which way CPO systems induce new challenges?



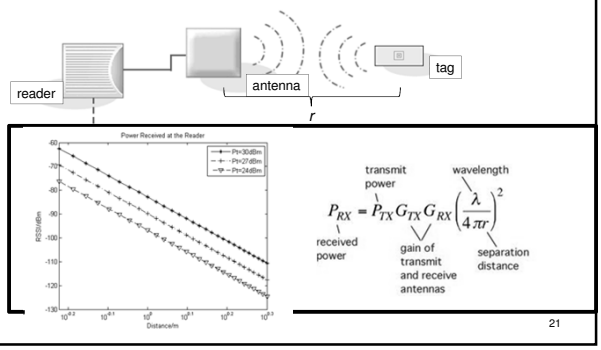
Observation

By being physical, CPOs are subject to physical laws and able to sense/interact with their physical environment

Physical law

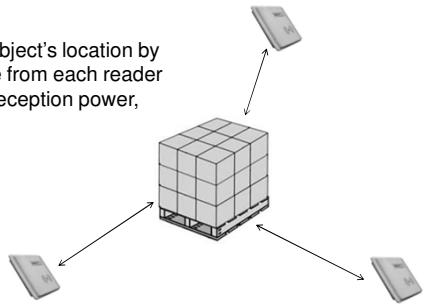


Physical law



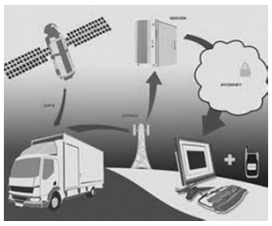
Indoor object tracking

Compute object's location by its distance from each reader based on reception power, e.g., RSSI.



Outdoor object tracking

Driver carries a smart phone



Sensing environment

accelerometer

About 35 percent of people over age 65 fall in their homes at least once each year. That figure increases to 50 percent for those with age 75 and over. -- Havard Health Letters 2009

Adaptive actions

accelerometer

- Raise an alarm
- Call her relatives
- Call her neighbors
- Call emergency services
- Contact her nearest hospital
- Call her family doctor
- Record the frequency

Adaptive actions

accelerometer

- Raise an alarm
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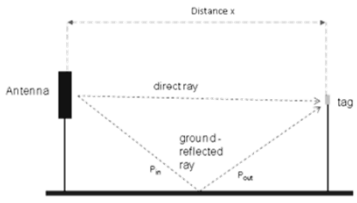
- Record the frequency

Subject to physical laws

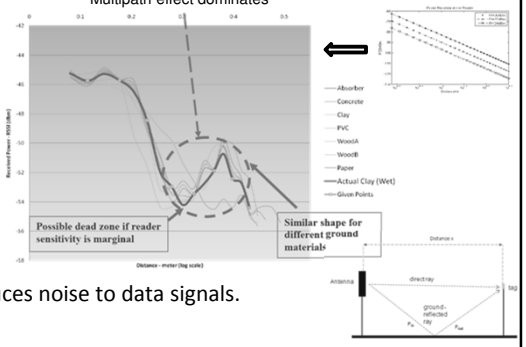
- Physical laws may induce undesirable effects.



Multi-path Effect

Subject to physical laws

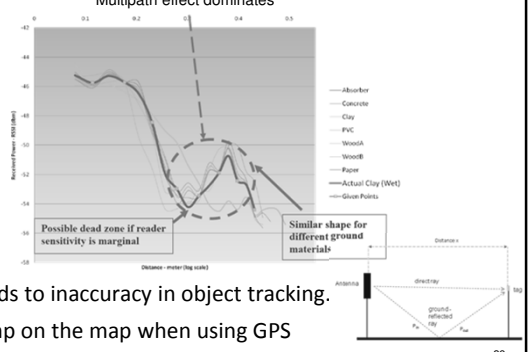
Multipath effect dominates



- Induces noise to data signals.

Subject to physical laws

Multipath effect dominates



- Leads to inaccuracy in object tracking.
- Jump on the map when using GPS

Induces engineering problem

Induces engineering problem

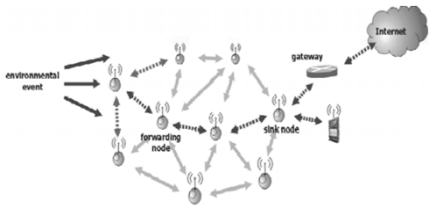
Is the problem common?

- For RFID data, the observed read rate (i.e., the percentage of tags in a reader's vicinity that are actually reported) in real-life deployment may drop down to the range of 60-70% [1]

[1] Jeffery, S.R., Garofalakis, M., and Frankin, M.J. Adaptive Cleaning for RFID Data Streams. In *Proceedings of the 32nd International Conference on Very Large Data Bases*, Seoul, Korea, September 2006, 163-174.

When objects are connected …

- Errors can be propagated from one to another.
- Sensitive information of an object can be derived from partial information held by its peers.



When objects are connected …

ON EVENT bird-detect (loc):

SELECT AVG (light), AVG (temp), event.loc
FROM sensors AS s
WHERE dist (s.loc, event.loc) < 10m
SAMPLE INTERVAL 2s FOR 30s

- Can we apply existing techniques on database application testing?

A nesC program for a WSN mote

```
#1: module OscilloscopeM {
#2:   provides interface StdControl;
#3:   uses {
#4:     interface Leds;
#5:     interface ADC as PhotoSensor;
#6:     interface ADC as TempSensor;
#7:     interface SendMsg; /* other interfaces */
#8:   }
#9: } implementation {
#10:   uint8_t packetReadingNumber;          // shared variable
#11:   // uint8_t lock = 0;
#12:   TOS_Msg msg;                          // shared variable
#13:   task void task4() { /* do something */ }
#14:   task void task3() { /* do something */ }
#15:   task void task2() {
#16:     OscopeMsg *pack;
#17:     static uint32_t i;
#18:     uint32_t start = i;
#19:     atomic {                            // atomic block
#20:       pack = (OscopeMsg *)msg.data;
#21:       packetReadingNumber = 0;
#22:       for (; i < start + 100000 && i < 200001; i++) { /* process sensing data */
#23:       }
#24:       if (i < 200001) {
#25:         post task2(); // post another instance to process remaining data
#26:         return;
#27:       } // else (finish processing the data): send the packet
#28:       i = 0;
#29:       pack->channel = 1;
#30:       pack->sourceMoteID = TOS_LOCAL_ADDRESS;
#31:       if (call SendMsg.send(TOS_UART_ADDR, sizeof(OscopeMsg), &msg)) {
#32:         call Leds.yellowToggle();
#33:       }
#34:     }
#35:     task void task1() { /* do something */
#36:       post task3();
#37:       post task4();
#38:     }
#39:     async event result_t PhotoSensor.dataReady(uint16_t data) {
#40:       OscopeMsg *pack;
#41:       // atomic { if (lock == 1) return; }
#42:       pack = (OscopeMsg *)msg.data;
#43:       atomic {
#44:         pack->data[packetReadingNumber++] = data;
#45:       }
#46:       if (packetReadingNumber == BUFFER_SIZE) {
#47:         // lock = 1;
#48:         post task2();
#49:       }
#50:       return SUCCESS;
#51:     }
#52:     event result_t SendMsg.sendDone(TOS_MsgPtr sent, result_t success) {
#53:       // atomic lock = 0; /* notify the availability of the message buffer */
#54:       return SUCCESS;
#55:     }
#56:     async event result_t TempSensor.dataReady(uint16_t data) { // do something
#57:       post task1();
#58:       return SUCCESS;
#59:     } /* other commands, events, and tasks */
#60: }
```

- How to learn the behavior of a mote?

Summary of challenges

- Data level
  - Ubiquitous sensing noises are not under full control.
  - Natural constraints on physical objects cannot be modeled completely and precisely.
- Logic level
  - Hardly able to consider adequately the real-life complexity of physical objects that are evolvable and noisy.
  - Unanticipated exceptions occur.

Summary of challenges

- Data level
  - Ubiquitous sensing noises are not under full control.
  - Natural constraints on physical objects cannot be modeled completely and precisely.
- Logic level
  - Need to consider adequately the real-life complexity of physical objects that are evolvable and noisy.
  - Need to prepare for unanticipated exceptions.

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Summary of challenges

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➔ Sensing defects

- Logic level
  - Need to consider adequately the real-life complexity of physical objects that are evolvable and noisy.
  - Need to prepare for unanticipated exceptions occur.

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Summary of challenges

- Data level
  - Ubiquitous sensing noises are not under full control.
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➔ Sensing defects

- Logic level
  - Need to consider adequately the real-life complexity of physical objects that are evolvable and noisy.

➔ Logic defects

  - Need to prepare for unanticipated exceptions occur.

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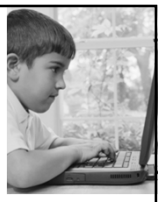

Jerry performs more search to check if these defects occur at other CPO systems.

Sensing defects

- Tasker is a popular Android app that performs user-defined tasks based on its environment changes (or situations).

An early bug (in v.20b):

- Failed to detect that wifi was inactive.
- Kept trying to establish connection.
- Drained battery power quickly.

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Adaptation defects

- Locale is an award-winning Android app that changes phone's settings based on pre-defined conditions.

An early bug (in v1.0):

- Mistake in condition evaluation.
- May bounced rapidly between adapted settings and default settings occasionally.
- Drained most of the phone processing power.
- Failed to respond to user inputs.

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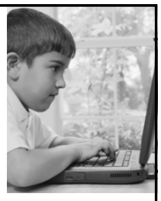
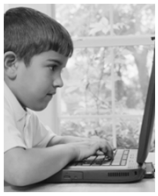


After collecting more bug reports, Jerry is interested in defect detection and management.

Defect detection and management

Jerry's story (Part III)



Defect detection

- In most cases, we don't have the ground truth.
- We are not able to tell if a sensed datum (or context) is correct.
  - The meaning of correct is unclear.
  - We need to live with some errors.
- CPO are subject to physical rules.
- Extract constraints that cover context changes from these rules.
- Catch context inconsistency upon rule violation.

Defect detection

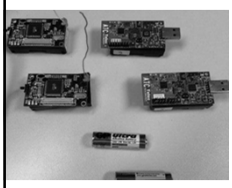
- Data level
  - Ubiquitous sensing noises are not under full control.
  - Natural constraints of physical objects cannot be modeled completely and precisely.

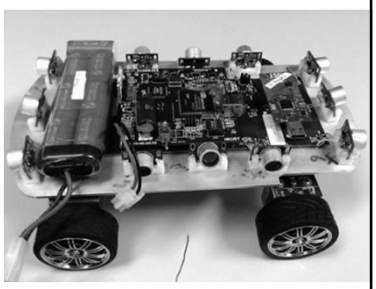
➔ Sensing defects

- Logic level
  - Need to consider adequately the real-life complexity of physical objects that are available for sensing.
  - Need to prepare for unanticipated exceptions occur.

➔ Logic defects

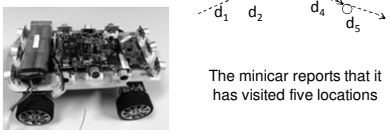
Illustrative Example





Illustrative Example

It is hard to tell which of the five contexts is/are incorrect unless we know the ground truth.

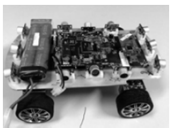


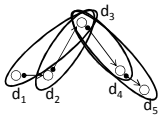
The minicar reports that it has visited five locations

Picture from http://www.thegreenhead.com/2007/09/motorized-walking-star-wars-lego-at-at.php

Illustrative Example

Constraint: The walking speed estimated from location changes should be less than 150% · v





The average speed obtained from the five contexts

Context changes

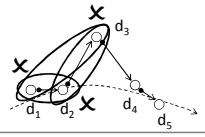
(d_1, d_3), (d_2, d_3), (d_3, d_4), (d_3, d_5)

violate the constraint

Four context inconsistencies found

Illustrative example

Drop-all resolution

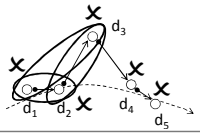


The overcautious nature makes this strategy tend to discard more contexts than necessary

d_3 is discarded, but d_1 and d_2 are discarded

Illustrative example

Drop-all resolution



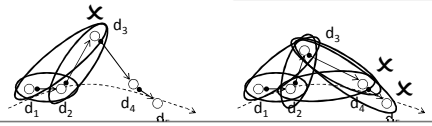
Lesson learnt: We should not discard all inconsistency-related contexts

All data are discarded

Illustrative example

Drop-latest resolution

Move d_3 closer to d_2



Deciding a context immediately to be correct / incorrect based on the nonexistence / existence of any context inconsistency may not give desirable results.

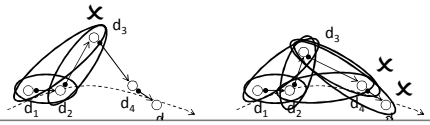
~~Context inconsistency (d_2, d_4)~~

~~Context inconsistency (d_3, d_5)~~

d_3 is kept, while d_4, d_5 are discarded

Illustrative example

Drop-latest resolution



Lesson learnt: We should not make decision based on a single inconsistency-related context.

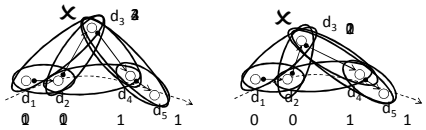
~~Context inconsistency (d_3, d_4)~~

~~Context inconsistency (d_3, d_5)~~

d_3 is kept, while d_4, d_5 are discarded

A possible resolution strategy

Heuristics: A context that participates more frequently in context inconsistencies is more likely to be incorrect



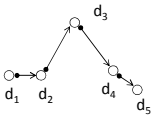
Context inconsistency (d_2, d_3)
Context inconsistency (d_1, d_3)
Context inconsistency (d_3, d_4)
Context inconsistency (d_3, d_5)

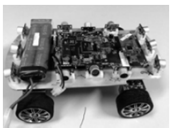
Context inconsistency (d_3, d_4)
Context inconsistency (d_3, d_5)

Illustrative example

Constraint: The walking speed estimated from location changes should be less than 150% · v

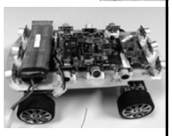
The average speed obtained from the five contexts





Useful constraints should be those that can affect the adaptive behavior of connected physical objects

Research questions



- How to identify useful constraints?
- How to formulate constraints?
- How to model contexts?
- Do we have a time window on the contexts?
- How to evaluate constraints in view of new contexts?
- May multiple context changes be evaluated in different order?
- Can the evaluation be incrementally done?
- What if constraints are changed dynamically?
- May context inconsistencies be automatically resolved?

[Xu et al. ESEC/FSE 2005, ICSE 2006, SEAMS 2007, ICDCS 2008, TOSEM 2010]

Defect detection

- Data level
  - Ubiquitous sensing noises are not under full control.
  - Natural constraints of physical objects cannot be modeled completely and precisely.

➔ Sensing defects

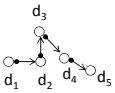
- Logic level
  - Need to consider adequately the real-life complexity of physical objects that are involved in the system.
  - Need to prepare for unanticipated exceptions occur.

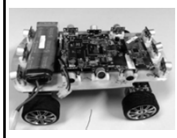
➔ Logic defects

What if logic defects?

Likely induce transient bugs

Hard to catch without a test oracle

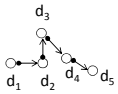




The minicar reports that it has visited five locations

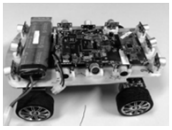
Learning-based defect detection

- Partition context streams into intervals
- Cluster these intervals based on their physical and logical features
- Intervals that cannot be clustered likely contain transient bugs



$d_1d_2d_3d_4d_5d_6$…….d_nd_{n+1}

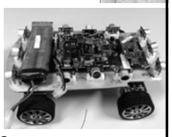
$|d_1d_2d_3d_4d_5|$ $|d_6$…$d_{12}|$ … $|$…$d_nd_{n+1}|$



The minicar reports that it has visited five locations

[Ngai et al. Ad Hoc Networks 2010; Tretmans SFM'11 2011; Zhou et al. ICDCS 2010]

Fault detection of adaptation logic



- How to model adaptation logic at design stage?
- Can we detect adaptation logic at design stage?
- What are adaptation design faults?
- What are the causes of adaptation design faults?
- Do these faults have patterns?
- Can we statically check adaptation design faults?
- Can we generate test cases for CPO systems from their design?
- Do we have new test coverage criteria for CPO systems?

[Lai et al. FSE 2008; Lu et al. FSE 2006; Sama et al. TSE 2010, JSS 2010; Wang et al. ICSE 2007]

Conclusion

CPO systems are written to:

- Bridge the gap between physical objects in daily lives and virtual objects in computers
  - No longer ***static data***, but ***dynamic objects*** that respect and address the evolvable, noisy reality
- Increase the participation and mobility of physical objects in pervasive computation
  - No longer ***passive data***, but ***active processes*** that interact with each other

More research challenges

[Ma, Baresi, Ghezzi et al. ESEC/FSE 2011]

- How to update adaptive components dynamically?
- May dynamical updates be made in peer-to-peer?
- How to model such requirements?
- What is the role of middleware?
- What is a test case?
- How to define test oracles in a CPO system?
- How to prevent failures from propagating among CPOs?
- How to learn the behavior of CPO systems?
- How to enforce security and privacy on CPO?

Dynamic reconfiguration and update

A video prepared by P.R. Kumar
Dept. of Electrical and Computer Engineering, and Coordinated Science Lab
University of Illinois, Urbana-Champaign

video

More research challenges

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The list is by no means exhaustive

More research challenges

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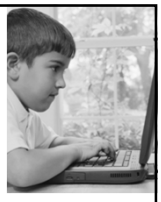
Solutions to these challenges can involve knowledge beyond software engineering and even computer science

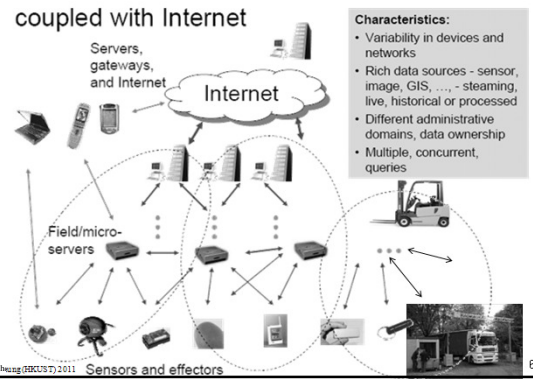
The Internet of Things



A video from IBM
[http://www.youtube.com/watch?v=sfEbMV295Kk]

video

Architecture in-the-large



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Some useful journals

- ACM Transactions on Software Engineering and Methodology
- ACM Transactions on Sensor Networks
- ACM Transactions on Embedded Computing Systems
- ACM Transactions on Computer Systems
- ACM Transactions on Programming Languages and Systems
- IEEE Transactions on Software Engineering
- IEEE Transactions on Computers
- IEEE Pervasive Computing
- Real Time Systems
- ACM Transactions on Intelligent Systems and Technology

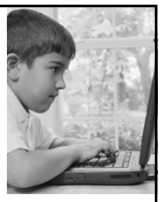
Some useful conferences

- ICSE, ESEC/FSE, ASE, Percom, Ubicom, ICDCS, RTSS, Sensys, EMSOFT, SIGMOD, VLDB, ICDE, FASE, …

Take home messages

- Take advantages of open-source projects
  - Identify real problems
    - Bug reports & discussion forums
  - Collect benchmark subjects
    - Code releases, JUnit tests, test drivers
- Get hands dirty
  - Do a few implementations
  - Get hands-on experience on real programs
  - There are many analysis tools available!!

Thank you



Grazie
Vielen Dank
Merci
Obrigado
Gracias
σας ευχαριστώ

Where is our Jerry?

Jerry's story (Part IV)

He graduated and started his enterpreneurship