TinyOS Tutorial

CSE521S, Spring 2017

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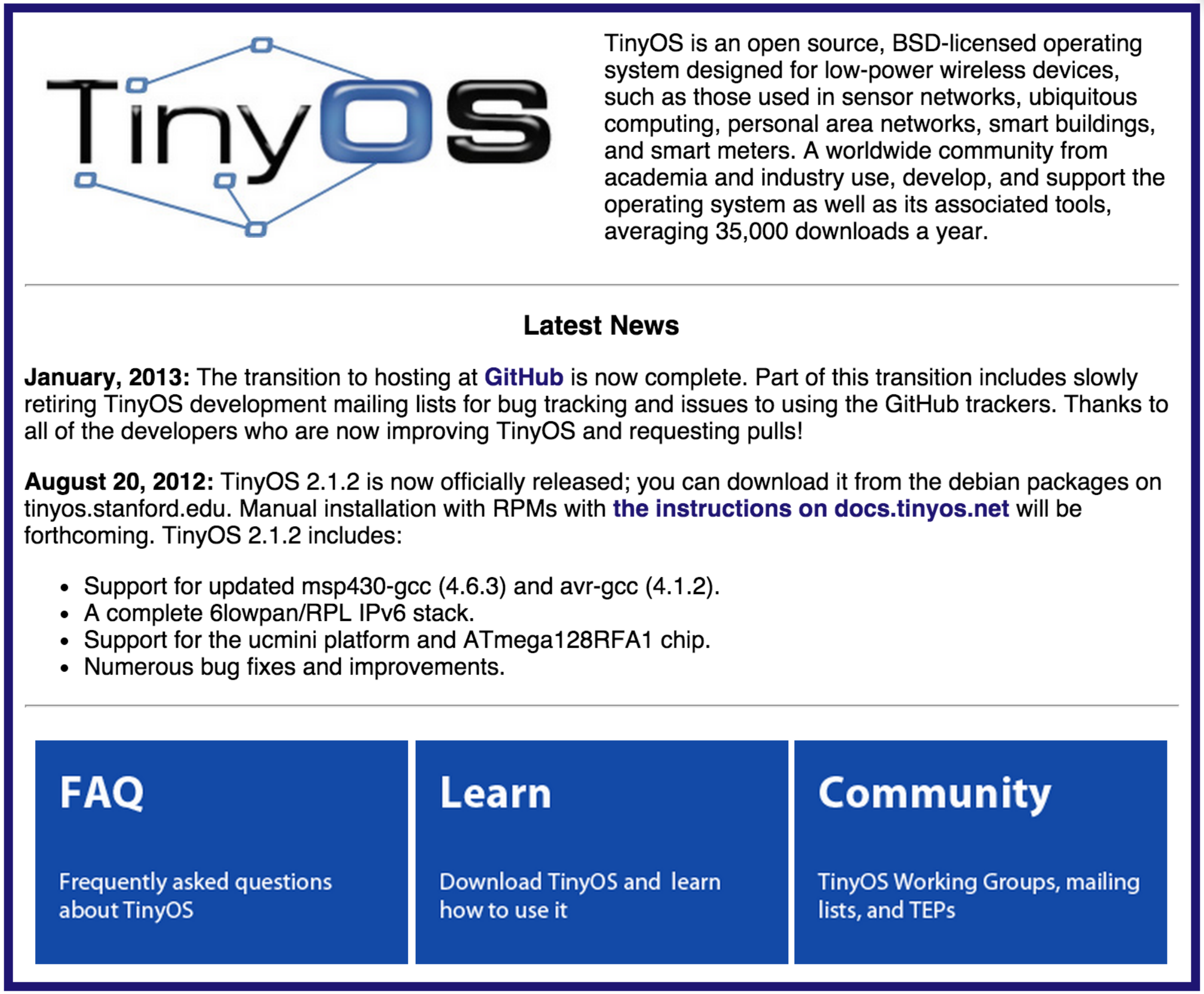
Based on tutorial by Mo Sha, Rahav Dor

TinyOS community

- http://www.tinyos.net/



TinyOS is an open source, BSD-licensed operating system designed for low-power wireless devices, such as those used in sensor networks, ubiquitous computing, personal area networks, smart buildings, and smart meters. A worldwide community from academia and industry use, develop, and support the operating system as well as its associated tools, averaging 35,000 downloads a year.

Latest News

January, 2013: The transition to hosting at **GitHub** is now complete. Part of this transition includes slowly retiring TinyOS development mailing lists for bug tracking and issues to using the GitHub trackers. Thanks to all of the developers who are now improving TinyOS and requesting pulls!

August 20, 2012: TinyOS 2.1.2 is now officially released; you can download it from the debian packages on tinyos.stanford.edu. Manual installation with RPMs with **the instructions on docs.tinyos.net** will be forthcoming. TinyOS 2.1.2 includes:

- Support for updated msp430-gcc (4.6.3) and avr-gcc (4.1.2).
- A complete 6lowpan/RPL IPv6 stack.
- Support for the ucmini platform and ATmega128RFA1 chip.
- Numerous bug fixes and improvements.

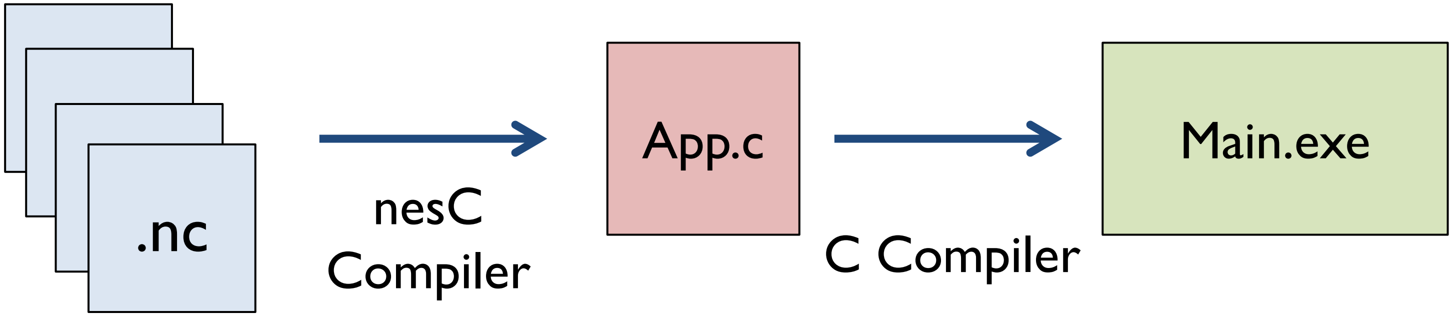
FAQ
Frequently asked questions about TinyOS
Learn
Download TinyOS and learn how to use it
Community
TinyOS Working Groups, mailing lists, and TEPs

Telosb / Tmote Sky

- CC2420 radio compatible with IEEE 802.15.4
- 250kbps data rate
- TI MSP430 microcontroller
  - 8MHz, 10kB RAM, 48k Flash
- Integrated antenna
  - Range 50m (indoor), 125m (outdoor)
- Integrated light, temperature, IR, humidity sensor

NesC

- Network Embedded System C
- Variation of C language
- Static language
  - ❑ No function pointers and no dynamic memory allocation



TinyOS Programming, Philip Levis

TinyOS Installation

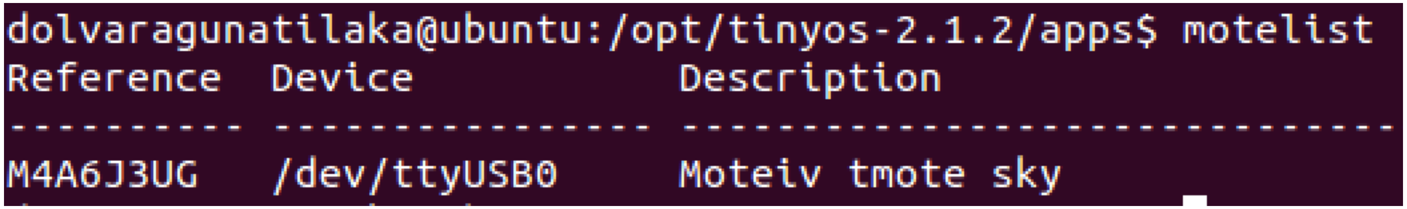
- TinyOS 2.1.2 Installation
  - ❑ Linux, Window, OSX

- Required Software
  - ❑ msp-430 tools
    - msp430-libc, binutils-msp430, gcc-msp430
  - ❑ NesC: https://github.com/tinyos/nesc.git
  - ❑ TinyOS: https://github.com/tinyos/tinyos-main.git

Connect motes

- Check your TinyOS installation
  - ❑ `tos-check-env`

- Check which port a mote attached to
  - ❑ `motelist`



```
dolvaragunatilaka@ubuntu:/opt/tinyos-2.1.2/apps$ motelist
Reference  Device           Description
---------- ---------------- ---------------------------------
M4A6J3UG   /dev/ttyUSB0     Moteiv tmote sky
```

- Give access permission
  - ❑ `sudo chmod 666 /dev/<devicename>`
  - ❑ `sudo gpasswd -a username dialout`

make System

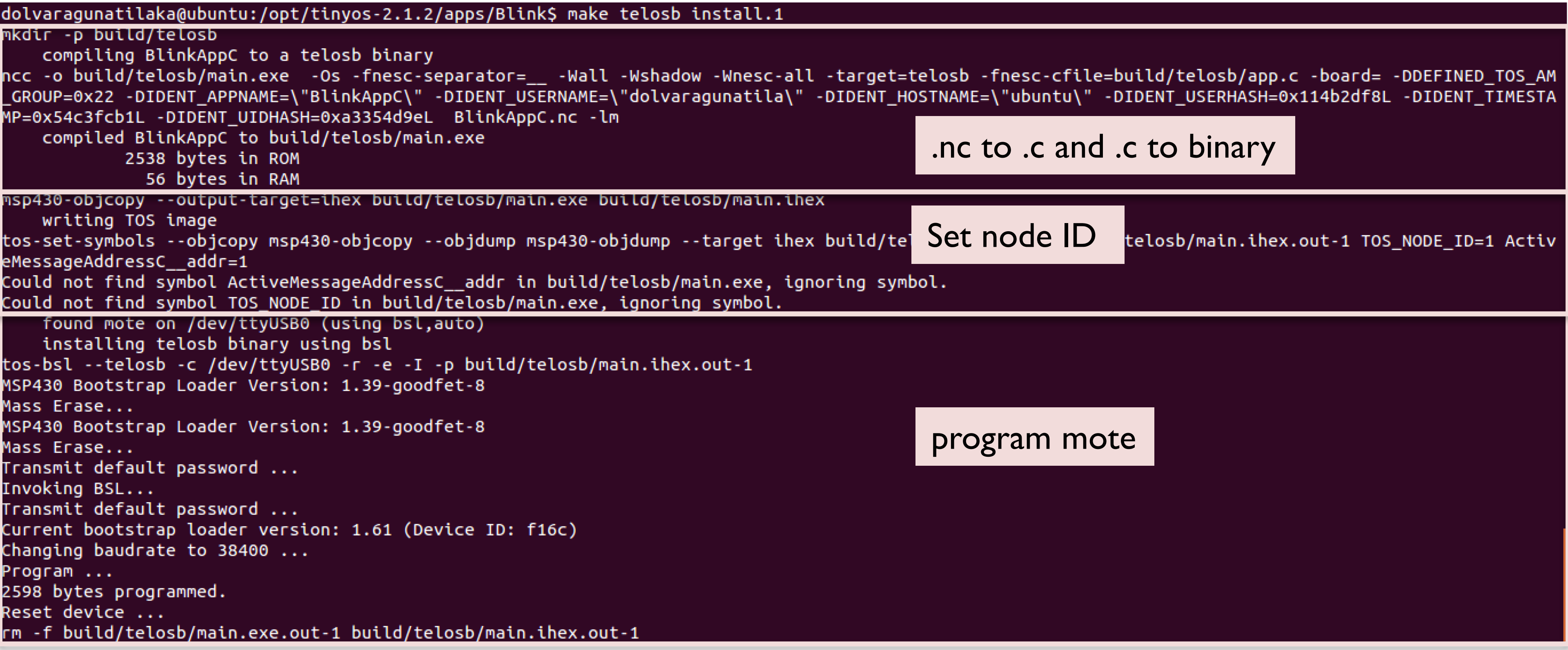
- TinyOS includes Makefiles to support the build process

```
COMPONENT=MainAppC
TINYOS_ROOT_DIR?=../..include
$(TINYOS_ROOT_DIR)/Makefile.include
```

- Compile an app without installing it on a mote:
  - ❑ **`make [platform]`**
  - ❑ Platform: telosb, micaz, mica2
- Install an app on a mote:
  - ❑ **`make [re]install.[node ID] [platform]`**
- Remove compiled files:
  - ❑ **`Make clean`**

Build Stages

```
make install.1 telosb
```



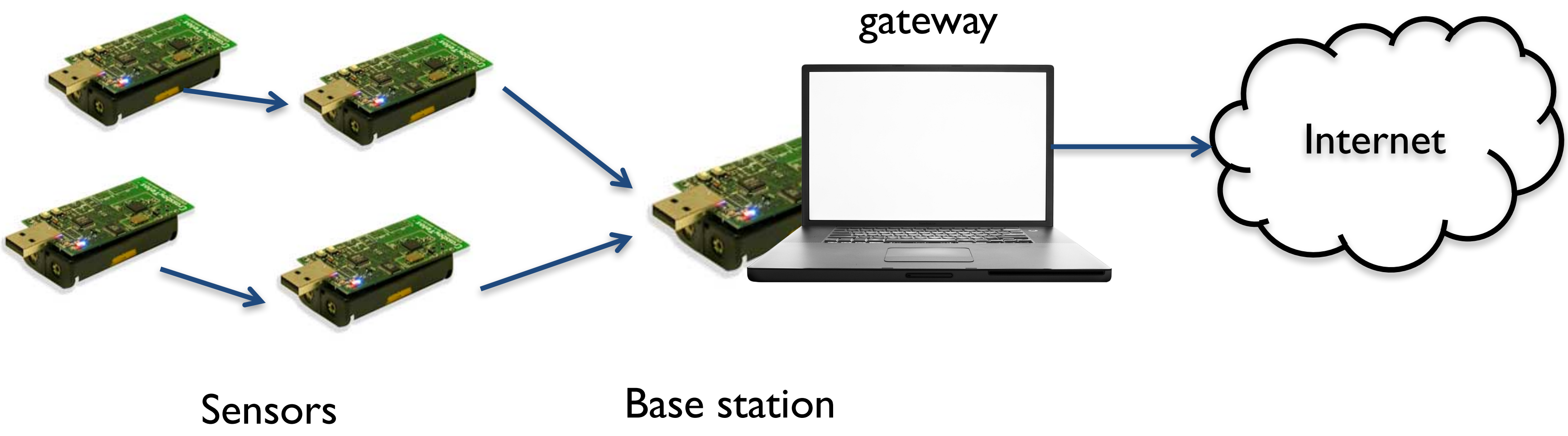
```
dolvaragunatilaka@ubuntu:/opt/tinyos-2.1.2/apps/Blink$ make telosb install.1
mkdir -p build/telosb
    compiling BlinkAppC to a telosb binary
ncc -o build/telosb/main.exe  -Os -fnesc-separator=__ -Wall -Wshadow -Wnesc-all -target=telosb -fnesc-cfile=build/telosb/app.c -board= -DDEFINED_TOS_AM
_GROUP=0x22 -DIDENT_APPNAME=\"BlinkAppC\" -DIDENT_USERNAME=\"dolvaragunatila\" -DIDENT_HOSTNAME=\"ubuntu\" -DIDENT_USERHASH=0x114b2df8L -DIDENT_TIMESTA
MP=0x54c3fcb1L -DIDENT_UIDHASH=0xa3354d9eL  BlinkAppC.nc -lm
    compiled BlinkAppC to build/telosb/main.exe
            2538 bytes in ROM
              56 bytes in RAM
msp430-objcopy --output-target=ihex build/telosb/main.exe build/telosb/main.ihex
    writing TOS image
tos-set-symbols --objcopy msp430-objcopy --objdump msp430-objdump --target ihex build/te                     telosb/main.ihex.out-1 TOS_NODE_ID=1 Activ
eMessageAddressC__addr=1
Could not find symbol ActiveMessageAddressC__addr in build/telosb/main.exe, ignoring symbol.
Could not find symbol TOS_NODE_ID in build/telosb/main.exe, ignoring symbol.
    found mote on /dev/ttyUSB0 (using bsl,auto)
    installing telosb binary using bsl
tos-bsl --telosb -c /dev/ttyUSB0 -r -e -I -p build/telosb/main.ihex.out-1
MSP430 Bootstrap Loader Version: 1.39-goodfet-8
Mass Erase...
MSP430 Bootstrap Loader Version: 1.39-goodfet-8
Mass Erase...
Transmit default password ...
Invoking BSL...
Transmit default password ...
Current bootstrap loader version: 1.61 (Device ID: f16c)
Changing baudrate to 38400 ...
Program ...
2598 bytes programmed.
Reset device ...
rm -f build/telosb/main.exe.out-1 build/telosb/main.ihex.out-1
```

.nc to .c and .c to binary

Set node ID

program mote

Sensor Network Architecture



TinyOS Design

- Component-based architecture
  - ❑ Components and interfaces
- Task and event-based concurrency
  - ❑ Task: deferred computation
  - ❑ Events: preempt the execution of a task or another event.
- Split-phase operation
  - ❑ Command returns immediately
  - ❑ Event signals completion

TinyOS Execution model

- To save energy, node stays asleep most of the time
- Task and event based concurrency:
  - Computation is kicked off by hardware interrupts
  - Interrupts may schedule tasks to be executed at some time in the future
  - TinyOS scheduler continues running until all tasks are cleared, then sends mote back to sleep

Event

TimerFired

Post task ReadSensor

ReadSensor

Components

- NesC application consists of one or more components
- A component *provides* and *uses* interfaces
- Components defined two scopes:
  - ❑ Modules: implementation of interfaces
  - ❑ Configurations: wiring interfaces of a component to interfaces provided by other components

```
configuration BlinkAppC
{
        provide interfaces
}
Implementation
{
        …
}
```

```
module BlinkC
{
        provides interfaces
        uses interfaces
}
Implementation
{
        …
}
```

Interfaces

- List of one or more functions

1. Generic interface
   - Take one or more types as a parameter

```
interface Queue<t> {
        …
    command t head();
    command t dequeue();
    command error_t enqueue(t newVal);
    command t element(uint8_t idx);
}
```

```
module QueueUserC
{
    uses interface Queue<uint32-t>;
}
```

Interfaces

2. Bidirectional
    - ❑ Commands and Events
    - ❑ Users call commands and providers signal events.

```
interface Receive
{
  event message_t * Receive(message_t * msg, void * payload, uint8_t len);
  command void * getPayload(message_t * msg, uint8_t * len);
  command uint8_t payloadLength(message_t * msg);
}
```

Component Scope - Modules

- Modules provide the implementation (logic) of one or more interfaces
- They may use other interfaces:

```
module ExampleModuleC
{
  provides interface SplitControl;
  uses interface Receive;
  uses interface Receive as OtherReceive;
}
implementation
{
  ...
}
```

Rename” interfaces with the as keyword -- required if you are using/providing more than one of the same interface!

`implementation`

- Variable declarations
- Helper functions
- Tasks
- Event handlers
- Command implementations

Modules: Variables and Functions

- Placed inside implementation block like standard C declarations:

```
...
implementation {
   uint8_t localVariable;
   void increment(uint8_t amount);   // declaration

   ...

   void increment(uint8_t amount) {  // implementation
     localVariable += amount;
   }
}
```

Modules: Tasks

- Look like functions, except:
  - Prefixed with task
  - Cannot return anything or accept any parameters
- Tasks are scheduled using the post keyword
- Can be preempted by interrupts, but not by other tasks
  - Design consideration: Break a series of long operations into multiple tasks

```
implementation {
 ...
 task void handlePacket()
 {
 }
}
```

```
post handlePacket();
```

Can post from within commands, events, and other tasks

Modules: Commands and Events

- Commands and events also look like C functions, except:
  - they start with the keyword command or event
  - the "function" name is in the form:

    InterfaceName.commandOrEventName

```
implementation {
  command error_t SplitControl.start()
  {
     // Implements SplitControl’s start() command
  }

  event message_t * Receive.receive(message_t * msg, void * payload, uint8_t len)
  {
     // Handles Receive’s receive() event
  }
}
```

Modules: Commands and Events

- Commands are invoked using the call keyword:

```
call Leds.led0Toggle();
// Invoke the led0Toggle command on the Leds interface
```

- Event handlers are invoked using the signal keyword:

```
signal SplitControl.startDone();
// Invoke the startDone event handler on the SplitControl interface
```

Component Scope - Configurations

- Connect components / wire interfaces

```
configuration NetworkHandlerC
{
   provides interface SplitControl;
   uses interface Receive;
}

implementation
{
   components NetworkHandlerC as NH,
              ActiveMessageP as AM;
   NH.Receive -> AM.Receive;
   SplitControl = NH.SplitControl;
}
```

-> wire to external interface

= wire to internal interface

Concurrency Model

- Task
  - deferred execution, run to completion
  - Does not preempt each other
- Event handler
  - Signal asynchronously by HW interrupt
  - Preempt tasks and other event handlers
  - Command/event uses `async` keyword
- Race condition: concurrent interrupt/task updates to shared states

Race conditions

1. Keep code synchronous (update shared state using task)
   - If timing isn't crucial, defer code to tasks (synchronous)

```
implementation {
  uint8_t sharedCounter;

  task void incrementCounter() {
    sharedCounter++;
  }

  async event void Alarm.fired() {
    post incrementCounter();
  }

  event void Receive.receive(...) {
    ...
    sharedCounter++;
  }
}
```

Task is scheduled immediately, but executed later

Race Condition

2. Atomic Block
   - Interrupts are disabled – use sparingly and make it short

```
implementation {
  uint8_t sharedCounter;

  async event void Alarm.fired() {
    atomic{
       sharedCounter++;
    }
  }
  async event void Alarm2.fired() {
   atomic{
       sharedCounter++;
    }
 }
}
```

Race Condition

- Compiler detects race condition -> false positive
- Absolutely sure that there is no race condition (or do not care if there is), use the norace keyword:

```
implementation {
  norace uint8_t sharedCounter;

  async event void Alarm1.fired() {
    sharedCounter++;
    call Alarm2.start(200);
  }

  async event void Alarm2.fired() {
    sharedCounter--;
    call Alarm1.start(200);
  }
}
```

Race condition is impossible; these Alarms are mutually exclusive

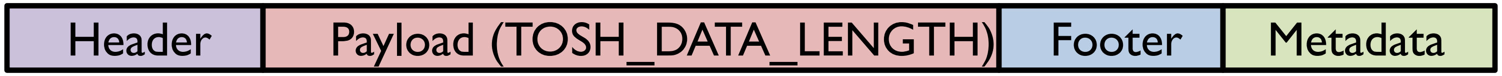
Network Communication

- Each node can have a unique 16-bit address (am_addr_t) specified on the make command
  - ❑ make install.**[address]** platform
- Two special address constants:
  - ❑ TOS_BCAST_ADDR (0xFFFF) is reserved for broadcast traffic
  - ❑ TOS_NODE_ID always refers to the node's own address
- 8-bit group ID to create virtual network/ subnetwork
- Each message also has an 8-bit Active Message ID (am_id_t) analogous to TCP ports
  - ❑ Determines how host should handle received packets, not which host receives it
  - ❑ 0 - 126 are reserved for TinyOS internal use

TinyOS Active Messages (AM)

- message_t structure
- Each platform defines platform-specific header, footer, and metadata fields for the message_t
- Applications can store up to TOSH_DATA_LENGTH bytes payload in the data field (28 by default, 114 max)

```
typedef nx_struct message_t {
  nx_uint8_t header[sizeof(message_header_t)];
  nx_uint8_t data[TOSH_DATA_LENGTH];
  nx_uint8_t footer[sizeof(message_footer_t)];
  nx_uint8_t metadata[sizeof(message_metadata_t)];
} message_t;
```



Header | Payload (TOSH_DATA_LENGTH) | Footer | Metadata

Split-Phase operation

- Many networking commands take a long time (ms) for underlying hardware operations to complete
- TinyOS makes these long-lived operations split-phase
  - ❑ Application issues start…() command that returns immediately
  - ❑ An event is signaled when it's actually done

```
interface SplitControl {
  command error_t start();
  event void startDone(error_t error);

  command error_t stop();
  event void stopDone(error_t error);
}
```

Error code here indicates how TinyOS *started* processing the request

Error code here indicates how TinyOS *completed* processing the request

Active Message Interface

send is a split-phase operation

```
interface AMSend {
   command error_t send(am_addr_t addr, message_t * msg,
      uint8_t len);
   event void sendDone(message_t * msg, error_t error);
   command error_t cancel(message_t * msg);
   command uint8_t maxPayloadLength();
   command void* getPayload(message_t * msg, uint8_t len);
}

interface Receive {
  event message_t* receive(message_t * msg, void *
    payload, uint8_t len);
}
```

Fired on another mote when packet arrives

Packet interface

```
interface Packet {
  command void clear(message_t * msg);

  command void* getPayload(message_t * msg, uint8_t
    len);

  command uint8_t payloadLength(message_t * msg);
  command void setPayLoadLength(message_t * msg, uint8_t
    len);

  command uint8_t maxPayloadLength();
}
```

Other networking interfaces

```
interface PacketAcknowledgements {
  async command error_t requestAck(message_t* msg);
  async command error_t noAck(message_t* msg);
  async command bool wasAcked(message_t* msg);
}
```

- Default behavior: no ACKs
- Even with ACKs enabled, no automatic retransmissions

Multi-Hop Routing

- Collection Tree Protocol (CTP)
  - ❑ Link estimator (based on ETX), routing engine, forwarding engine
- Dissemination Protocol
- Berkeley Low-Power IP Stack (BLIP) - 6LowPANs
  - ❑ IP Routing over 802.15.4
  - ❑ Adaptation layer
    - Header compression
    - Fragmentation

802.15.4 Radio Channels

- Use ISM 2.4 GHz band
- Consist of 16 channels (11-26)
- Lead to interference between motes and 802.11, Bluetooth, etc. devices.

Changing Channel

- Default is channel 26
- Command-line: `CC2420_CHANNEL=xx make [platform]`
- makefile: `PFLAGS = -DCC2420_DEF_CHANNEL=xx`
- Run-time:
  - ❑ **`CC2420ControlC`** component

```
interface CC2420Config
{
        command uint8_t getChannel();
        command void setChannel(uint8_t channel);
        command error_t sync();
        event void syncDone(error_t error);
                …
}
```

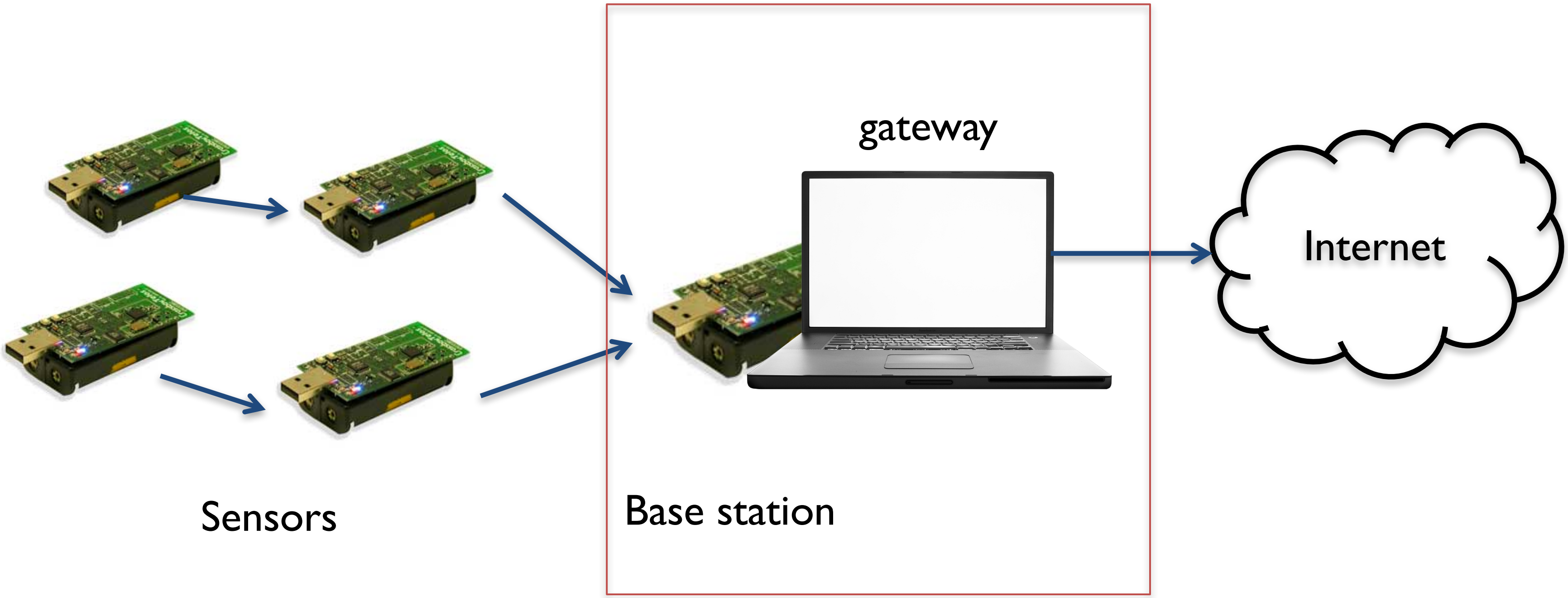
Obtaining Sensor Data

- Each sensor components provides one or more split-phase Read interfaces

```
interface Read<val_t> {
  command error_t read();
  event void readDone(error_t result, val_t val);
}
```

- Some sensor drivers provide additional interfaces for bulk (ReadStream) or low-latency (ReadNow) readings
- Sensor components are stored in:
  - $TOSROOT/tos/platform/[platform]

Sensor Network Architecture



Mote -PC Communication

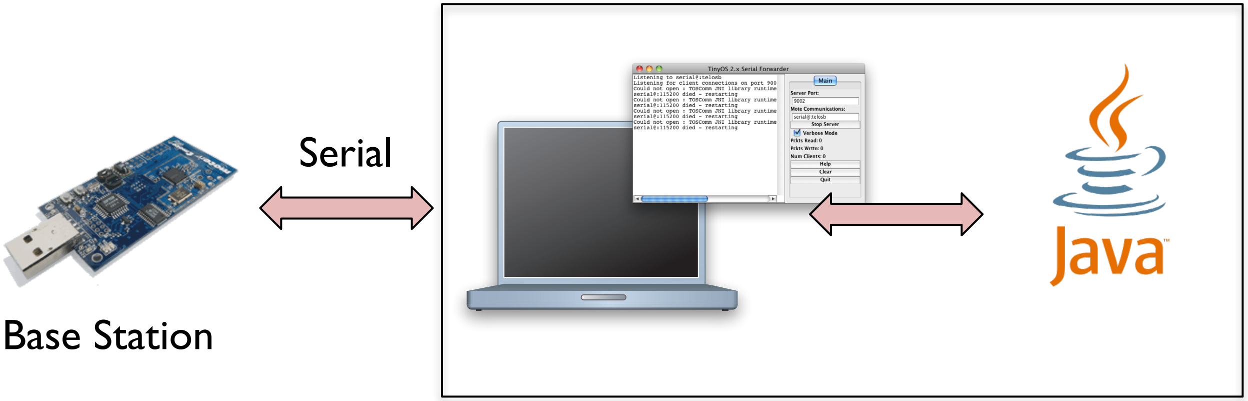
- TinyOS apps can send or receive data over the serial/USB connection to/from an attached PC

- The SerialActiveMessageC component provides an Active Messaging interface to the serial port:

```
components SerialActiveMessageC;
MyAppP.SerialAMSend ->SerialActiveMessageC.Send[AM_SENSORREADING];
MyAppP.SerialReceive ->SerialActiveMessageC.Receive[AM_SENSORREADING];

MyAppP.SerialPowerControl -> SerialActiveMessageC;
```

Mote-PC Serial Communication



Base Station

Serial

TinyOS 2.x Serial Forwarder

```
Listening to serial@:telosb
Listening for client connections on port 900
Could not open : TOSComm JNI library runtime
serial@:115200 died - restarting
Could not open : TOSComm JNI library runtime
serial@:115200 died - restarting
Could not open : TOSComm JNI library runtime
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Could not open : TOSComm JNI library runtime
serial@:115200 died - restarting
```

Server Port: 9002

Mote Communications: serial@:telosb

☑ Verbose Mode

Pckts Read: 0

Pckts Wrttn: 0

Num Clients: 0

- Print Raw Packets using Java Listen Tool

```
java net.tinyos.tools.Listen -comm
serial@/dev/ttyUSB0:telosb
```

packet source

Serial Forwarder

- Java SDK connects to SerialForwarder and converts TinyOS messages to/from native Java objects.

```
java net.tinyos.sf.SerialForwarder -comm
    serial@[port]:[speed]
```

- Let’s applications connect to it over a TCP/IP stream in order to use that packet source (serial port)

- `mig` application auto-generates message object from packet description

```
mig java -java-classname=[classname]
[header.h] [message-name] –o [classname].java
```

TOSSIM

- Simulate TinyOS applications
- Good way to rapidly test application logic, at the cost of some realism
  - e.g., does not emulate sensing and does not reproduce timing of real microcontrollers
- Besides app code, need two configuration details:
  - *Topology* of simulated network – e.g. signal strength
  - *Noise trace* from environment - e.g. ambient noise

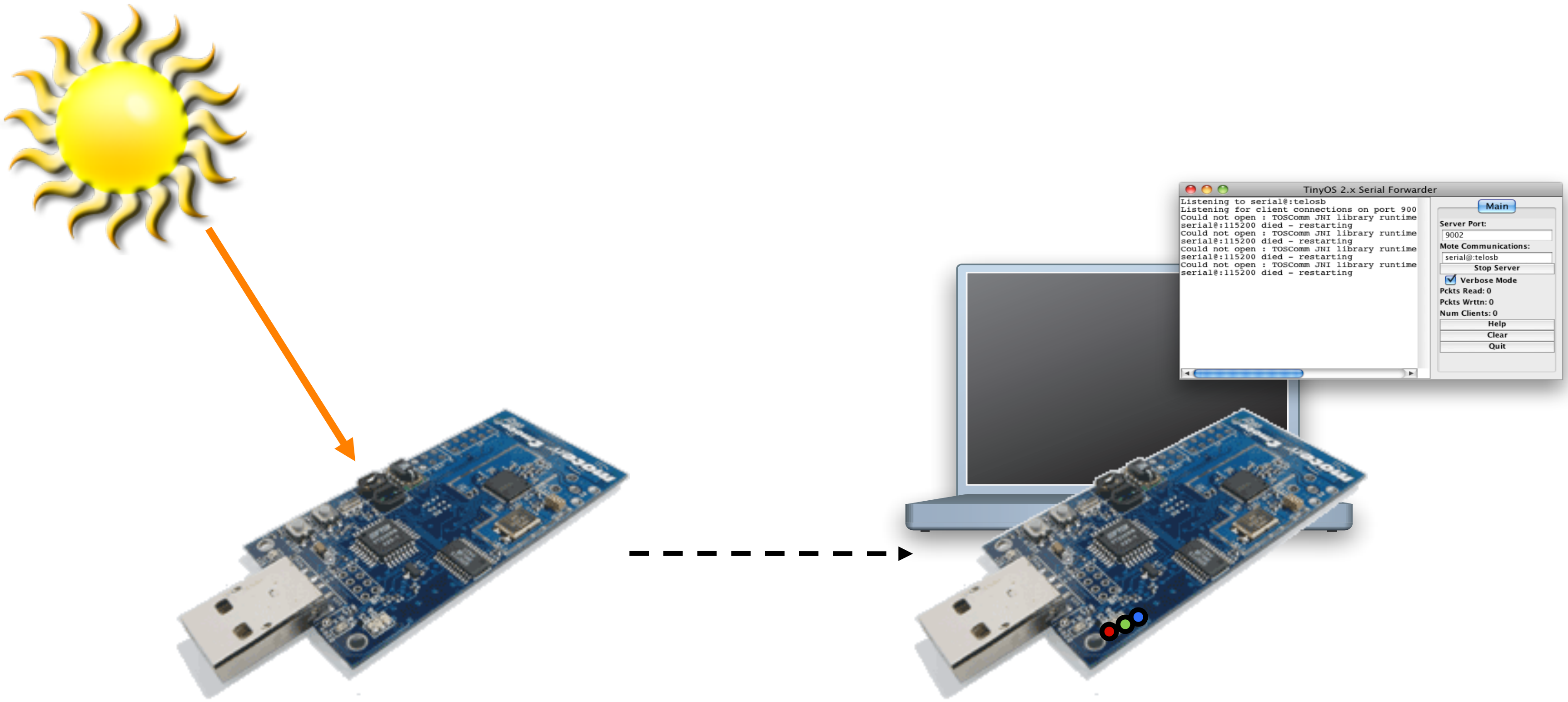
```
0   1   -90.80
1   0   -95.95
0   2   -97.48
2   0   -102.10
0   3   -111.33
3   0   -115.49
0   4   -104.82
4   0   -110.09
...
```

(from 15-15-sparse-mica2-grid.txt)

```
-39
-98
-98
-98
-99
-98
-94
-98
...
```

(from meyer-heavy.txt)

Putting it All Together



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```

Server Port: 9002

Mote Communications: serial@:telosb

☑ Verbose Mode

Pckts Read: 0

Pckts Wrttn: 0

Num Clients: 0

Demo

- DemoMessage.h
- DemoAppC.nc (configuration)
- DemoP.nc (module)
- Makefile
- JAVA
  - ❑ Main.java
  - ❑ Makefile

Makefile

```
COMPONENT=DemoAppC
TINYOS_ROOT_DIR?=../..include
$(TINYOS_ROOT_DIR)/Makefile.include
```

DemoMessege.h

- Define a new message type

```
#ifndef __DEMOAPP_H
#define __DEMOAPP_H
enum
{
    AM_DEMO_MESSAGE = 150,
};
typedef nx_struct demo_message
{
    uint16_t photoReading;
} demo_message_t;

#endif // __DEMOAPP_H
```

DemoAppC.nc

```
#include "DemoApp.h"
configuration DemoAppC{}
implementation
{
     components DemoP, MainC, new HamamatsuS10871TsrC() as PhotoC;
     components ActiveMessageC;
     components new AMSenderC(AM_DEMO_MESSAGE), new AMReceiverC(AM_DEMO_MESSAGE);
     components LedsC;
     components new TimerMilliC();
     components SerialActiveMessageC as SerialC;

     DemoP.Boot -> MainC;
     DemoP.Photo -> PhotoC;
     DemoP.RadioControl -> ActiveMessageC;
     DemoP.AMSend -> AMSenderC;
     DemoP.Receive -> AMReceiverC;
     DemoP.Packet -> ActiveMessageC;
     DemoP.SerialControl -> SerialC;
     DemoP.SerialAMSend -> SerialC.AMSend[AM_DEMO_MESSAGE];
     DemoP.SerialPacket -> SerialC;
     DemoP.Leds -> LedsC;
     DemoP.Timer -> TimerMilliC;
}
```

DemoP.nc

```
module DemoP
{
    uses interface Boot;
    uses interface Read<uint16_t> as Photo;
    uses interface SplitControl as RadioControl;
    uses interface AMSend;
    uses interface Receive;
    uses interface Packet;
    uses interface SplitControl as SerialControl;
    uses interface Packet as SerialPacket;
    uses interface AMSend as SerialAMSend;
    uses interface Leds;
    uses interface Timer<TMilli>;
}
implementation
{
    message_t buf;
    message_t *receivedBuf;
    task void readSensor();
    task void sendPacket();
    task void sendSerialPacket();
```

DemoP.nc

```
event void Boot.booted()
{
    call RadioControl.start();
    call SerialControl.start();
}

event void RadioControl.startDone(error_t err)
{
    if(TOS_NODE_ID == 0) // sender
        call Timer.startPeriodic(256);
}
event void Timer.fired()
{
    post readSensor();
}
event void RadioControl.stopDone(error_t err){}
event void SerialControl.startDone(error_t err){}
event void SerialControl.stopDone(error_t err){}
```

DemoP.nc

```
task void readSensor()
{
    if(call Photo.read() != SUCCESS)
        post readSensor();
}
event void Photo.readDone(error_t err, uint16_t value)
{
    if(err != SUCCESS)
        post readSensor();
    else
    {
        demo_message_t * payload = (demo_message_t *)call
                Packet.getPayload(&buf,sizeof(demo_message_t));

        payload->photoReading = value;
        post sendPacket();
    }
}
```

DemoP.nc

```
task void sendPacket()
{
    if(call AMSend.send(AM_BROADCAST_ADDR, &buf,
sizeof(demo_message_t)) != SUCCESS)
        post sendPacket();
}
event void AMSend.sendDone(message_t * msg, error_t err)
{
    if(err != SUCCESS)
        post sendPacket();
}
```

DemoP.nc (Receiver)

```
event message_t * Receive.receive(message_t * msg, void * payload, uint8_t len)
{
    demo_message_t * demoPayload = (demo_message_t *)payload;
    call Leds.set(demoPayload->photoReading / 200);
    receivedBuf = msg;
    post sendSerialPacket();
    return msg;
}
task void sendSerialPacket()
{
    if(call SerialAMSend.send(AM_BROADCAST_ADDR, receivedBuf,
sizeof(demo_message_t))! = SUCCESS)
        post sendSerialPacket();
}
event void SerialAMSend.sendDone(message_t* ptr, error_t success)
{
    if(success!=SUCCESS)
        post sendSerialPacket();
}
```

Java Makefile

- mig command auto-generates DemoAppmsg class

```
BUILD_EXTRA_DEPS = Main.class

Main.class: DemoAppMsg.java
    javac *.java

DemoAppMsg.java: ../DemoApp.h
    nescc-mig java -java-classname=DemoAppMsg ../DemoApp.h
    demo_message -o $@

clean:
    rm -f DemoAppMsg.java  *.class
```

Main.java

```
import java.io.*;
import net.tinyos.message.*;
public class Main implements MessageListener
{
    MoteIF mote;
    PrintStream outputFile = null;
    public Main()
    {
        try {
            mote = new MoteIF();
            mote.registerListener(new DemoAppMsg(), this);
        }
         catch(Exception e) {}
    }
    public void messageReceived(int dest, Message m)
     {
        DemoAppMsg msg = (DemoAppMsg)m;
        String output = (msg.get_photoReading());
        System.out.println("reading: " +output);
    }
    …
```