cis32-ai — lecture # 6 — tue-21-feb-2006

today's topics:

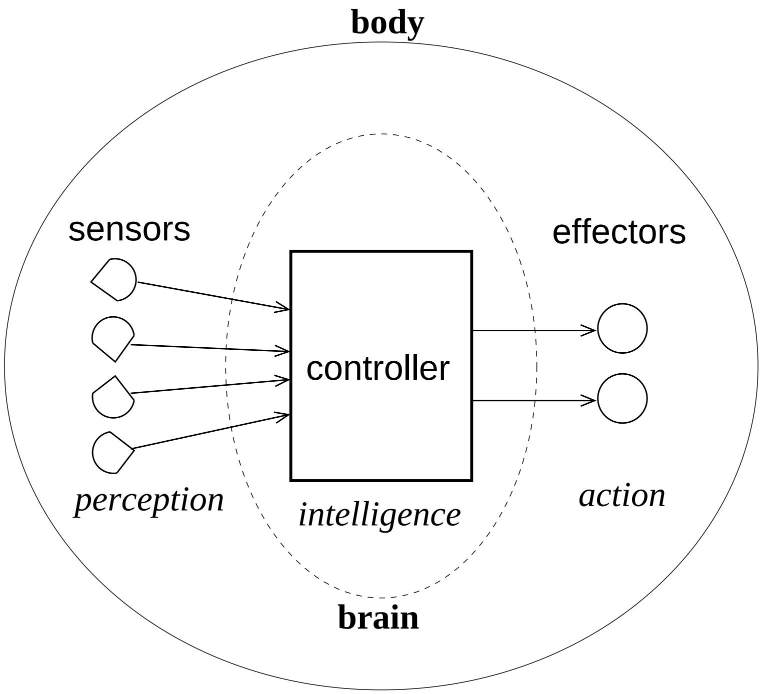
- introduction to robotics

(1) autonomous agents and autonomous robotics.

- we will be discussing *autonomous mobile robots*
- what is a robot?
  - "a programmable, multifunction manipulator designed to move material, parts, tools or specific devices through variable programmed motions for the performance of various tasks." [Robot Institute of America]
  - "an active, artificial *agent* whose environment is the physical world" [Russell&Norvig, p773]
- what is an agent?
  - "anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors." [Russell&Norvig, p32]
- what is autonomy?
  - no remote control!!
  - an agent makes decisions on its own, guided by feedback from its sensors; but you write the program that tells the agent how to make its decisions environment.

(1) our definition of a *robot*.

- *robot* = *autonomous embodied agent*
- has a *body* and a *brain*
- exists in the physical world (rather than the virtual or simulated world)
- is a mechanical device
- contains *sensors* to perceive its own state
- contains *sensors* to perceive its surrounding environment
- possesses *effectors* which perform actions
- has a *controller* which takes input from the sensors, makes *intelligent* decisions about actions to take, and effects those actions by sending commands to motors



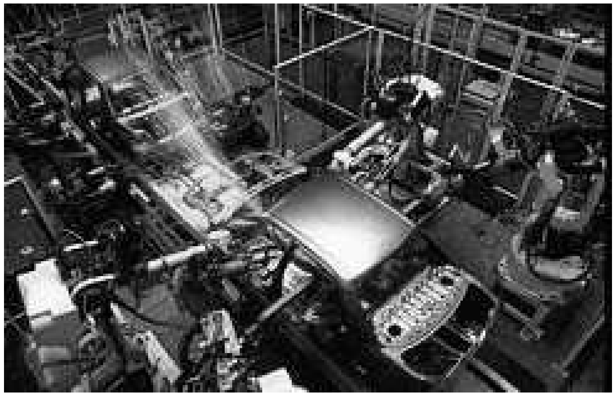
our canonical agent

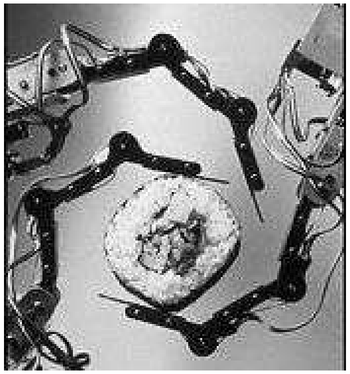
(1) a bit of robot history.

- the word *robot* came from the Czech word *robota*, which means *slave*
- used first by playwrite Karel Capek, "Rossum's Universal Robots" (1923)
- human-like automated devices date as far back as ancient Greece
- modern view of a robot stems from science fiction literature
- foremost author: Isaac Asimov, "I, Robot" (1950)
- the *Three Laws of Robotics*
  1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.
  2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
  3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
- Hollywood broke these rules: e.g., "The Terminator" (1984)

(1) effectors.

- comprises all the mechanisms through which a robot can *effect* changes on itself or its environment
- *actuator* = the actual mechanism that enables the effector to execute an action; converts software commands into physical motion
- types:
  - arm
  - leg
  - wheel
  - gripper
- categories:
  - *manipulator*
  - *mobile*

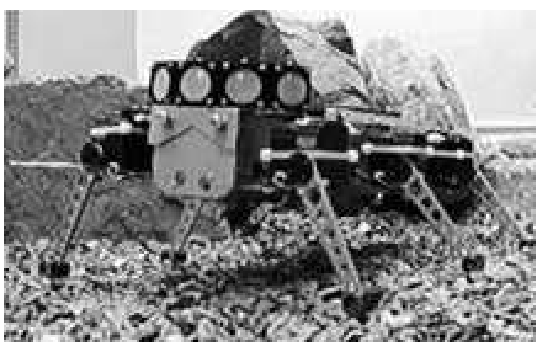


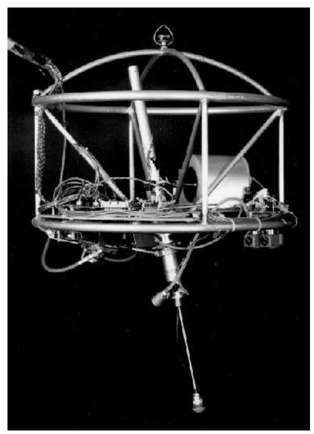


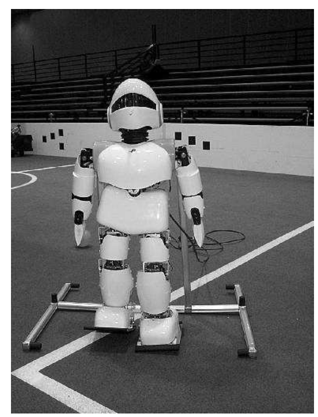
some manipulator robots

(1) mobile robots.

- classified by manner of locomotion:
  - *wheeled*
  - *legged*
- stability is important
  - *static stability*
  - *dynamic stability*







(1) *degrees of freedom*.

- number of directions in which robot motion can be controlled
- free body in space has 6 degrees of freedom:
  - three for position (x, y, z)
  - three for orientation $(roll, pitch, yaw)$
    - yaw refers to the direction in which the body is facing
      i.e., its orientation within the xy plane
    - $roll$ refers to whether the body is upside-down or not
      i.e., its orientation within the yz plane
    - $pitch$ refers to whether the body is tilted
      i.e., its orientation within the xz plane
- if there is an actuator for every degree of freedom, then all degrees of freedom are controllable $\Rightarrow$ *holonomic*
- most robots are *non-holonomic*

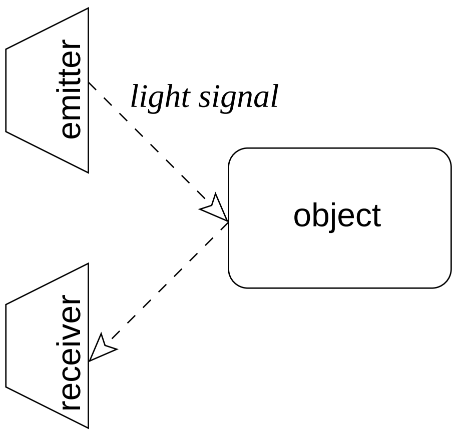
(1) sensors.

- $\Rightarrow$ perception
  - *proprioceptive:* know where your joints/sensors are
  - *odometry:* know where you are
- function: to convert a physical property into an electronic signal which can be interpreted by the robot in a useful way

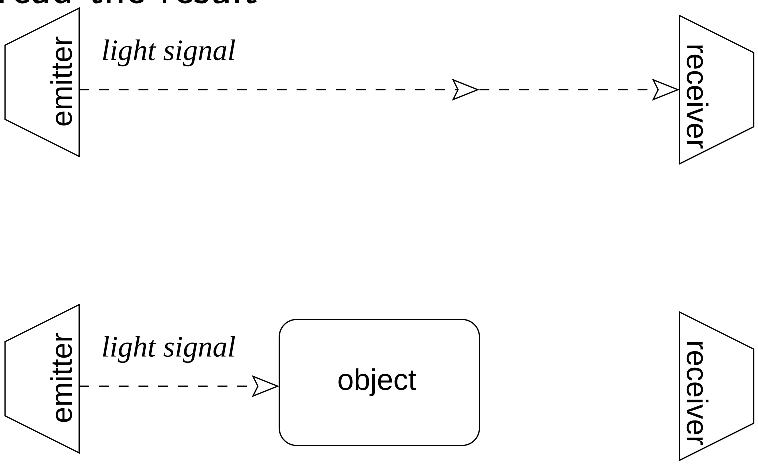
property being sensed	type of sensor
contact	bump, switch
distance	ultrasound, radar, infra red (IR)
light level	photo cell, camera
sound level	microphone
smell	chemical
temperature	thermal
inclination	gyroscope
rotation	encoder
pressure	pressure gauge
altitude	altimeter

(1) more on sensors.

- operation
  - *passive*: read a property of the environment
  - *active*: act on the environment and read the result



reflectance



break-beam

- noise
  - *internal*: from inside the robot
  - *external*: from the robot's environment
  - *calibration*: can help eliminate/reduce noise

(1) environment.

- *accessible* vs *inaccessible*
  - robot has access to all necessary information required to make an informed decision about to do next
- *deterministic* vs *nondeterministic*
  - any action that a robot undertakes has only one possible outcome.
- *episodic* vs *non-episodic*
  - the world proceeds as a series of repeated episodes.
- *static* vs *dynamic*
  - the world changes by itself, not only due to actions effected by the robot
- *discrete* vs *continuous*
  - sensor readings and actions have a discrete set of values.

(1) state.

- knowledge about oneself and one's environment
  - *kinematics* = study of correspondance between actuator mechanisms and resulting motion
    - motion:
      - rotary
      - linear
  - combines sensing and acting
  - *did i go as far as i think i went?*
- but one's environment is full of information
- for an agent, what is relevant?

(1) control.

- autonomy
- problem solving
- modeling
  - knowledge
  - representation
- control architectures
- deliberative control
- reactive control
- hybrid control

(1) autonomy.

- to be truly autonomous, it is not enough for a system simply to establish direct numerical relations between sensor inputs and effector outputs
- a system must be able to accomplish *goals*
- a system must be able to *solve problems*
- $\Rightarrow$ need to represent problem space
  - which contains goals
  - and intermediate states
- there is always a trade-off between *generality* and *efficiency*
  - more specialized $\Rightarrow$ more efficient
  - more generalized $\Rightarrow$ less efficient

(1) problem solving: example.

- GPS = General Problem Solver [Newell and Simon 1963]
- Means-Ends analysis

operator	*preconditions*	*results*
$PUSH(obj, loc)$	$at(robot, obj) \wedge large(obj) \wedge$ $clear(obj) \wedge armempty()$	$at(obj, loc) \wedge$ $at(robot, loc)$
$CARRY(obj, loc)$	$at(robot, obj) \wedge small(obj)$	$at(obj, loc) \wedge$ $at(robot, loc)$
$WALK(loc)$	$none$	$at(robot, loc)$
$PICKUP(obj)$	$at(robot, obj)$	$holding(obj)$
$PUTDOWN(obj)$	$holding(obj)$	$\neg holding(obj)$
$PLACE(obj1, obj2)$	$at(robot, obj2) \wedge holding(obj1)$	$on(obj1, obj2)$

(1) modeling the robot's environment.

- modeling
  - the way in which *domain knowledge* is embedded into a control system
  - information about the environment stored internally: *internal representation*
  - e.g., maze: robot stores a *map* of the maze "in its head"
- knowledge
  - information in a context
  - organized so it can be readily applied
  - understanding, awareness or familiarity acquired through learning or experience
  - physical structures which have correlations with aspects of the environment and thus have a predictive power for the system

(1) memory.

- divided into 2 categories according to duration
- *short term memory (STM)*
  - transitory
  - used as a buffer to store only recent sensory data
  - data used by only one behaviour
  - examples:
    - *avoid-past*: avoid recently visited places to encourage exploration of novel areas
    - *wall-memory*: store past sensor readings to increase correctness of wall detection
- *long term memory (LTM)*
  - persistent
  - *metric maps*: use absolute measurements and coordinate systems
  - *qualitative maps*: use landmarks and their relationships
  - examples:
    - *Markov models*: graph representation which can be augmented with probabilities for each action associated with each sensed state

(1) knowledge representation.

- must have a relationship to the environment (temporal, spatial)
- must enable predictive power (look-ahead), but if inaccurate, it can deceive the system
- *explicit*: symbolic, discrete, manipulable
- *implicit*: embedded within the system
- *symbolic*: connecting the meaning (semantics) of an arbitrary symbol to the real world
- difficult because:
  - sensors provide signals, not symbols
  - symbols are often defined with other symbols (circular, recursive)
  - requires interaction with the world, which is noisy
- other factors
  - speed of sensors
  - response time of effectors

(1) components of knowledge representation.

- *state*
  - totally vs partially vs un- observable
  - discrete vs continuous
  - static vs dynamic
- *spatial*: navigable surroundings and their structure; metric or topological maps
- *objects*: categories and/or instances of detectable things in the world
- *actions*: outcomes of specific actions on the self and the environment
- *self/ego*: stored proprioception (sensing internal state), self-limitations, capabilities
  - *perceptive*: how to sense
  - *behaviour*: how to act
- *intentional*: goals, intended actions, plans
- *symbolic*: abstract encoding of state/information

(1) types of representations.

- maps
  - *euclidean map*
    - represents each point in space according to its metric distance to all other points in the space
  - *topological map*
    - represents locations and their connections, i.e., how/if they can be reached from one another; but does not contain exact metrics
  - *cognitive map*
    - represents behaviours; can store both previous experience and use for action
    - used by animals that forage and home (animal navigation)
    - may be simple collections of vectors
- graphs
  - nodes and links
- Markov models
  - associates probabilities with states and actions

(1) control architecture.

- a control architecture provides a set of principles for organizing a control system
- provides structure
- provides constraints
- refers to software control level, not hardware!
- implemented in a programming language
- don't confuse "programming language" with "robot architecture"
- architecture guides how programs are structured

(1) classes of robot control architectures.

- *deliberative*
  - look-ahead; think, plan, then act
- *reactive*
  - don't think, don't look ahead, just react!
- *hybrid*
  - think but still act quickly
- *behaviour-based*
  - distribute thinking over acting

(1) deliberative control.

- classical control architecture (first to be tried)
- first used in AI to reason about actions in non-physical domains (like chess)
- natural to use this in robotics at first
- example: Shakey (1960's, SRI)
  - state-of-the-art machine vision used to process visual information
  - used classical planner (STRIPS)
- planner-based architecture
  1. sensing (S)
  2. planning (P)
  3. acting (A)
- requirements
  - lots of time to think
  - lots of memory
  - (but the environment changes while the controller thinks)

(1) reactive control.

- operate on a short time scale
- does not look ahead
- based on a tight loop connecting the robot's sensors with its effectors
- purely reactive controllers do not use any internal representation; they merely react to the current sensory information
- collection of rules that map situations to actions
  - simplest form: divide the perceptual world into a set of mutually exclusive situations recognize which situation we are in and react to it
  - (but this is hard to do!)
- example: subsumption architecture (Brooks, 1986)
  - hierarchical, layered model

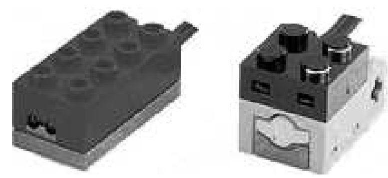
(1) hybrid control.

- use the best of both worlds (deliberative and reactive)
- combine open-loop and closed-loop execution
- combine different time scales and representations
- typically consists of three layers:
  1. reactive layer
  2. planner (deliberative layer)
  3. integration layer to combine them
  4. (but this is hard to do!)

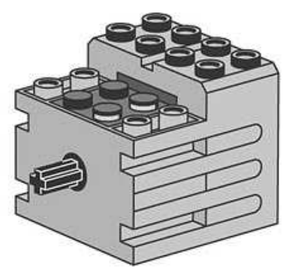
(2) LEGO Mindstorms.

- Hitachi h8300 microprocessor called RCX
- with an IR transceiver

- and 3 input ports, for:
  - light sensor
  - touch sensor



- and 3 output ports, for:
  - motors
  - light bulbs



(2) programming the LEGO Mindstorms.

- you write programs on your computer and *download* them to the RCX using an IR transmitter ("communication tower")

- Mindstorms comes with RoboLab — graphical programming environment
- but people have built other interfaces, e.g.:
  - Not-Quite C (NQC)
  - Brickos
  - lejos

(2) Not-Quite C.

- programming language based on C which runs on the RCX
- first you need to download *firmware* onto the RCX so that it will understand the NQC code which you write
- then you can write programs
- NQC is mostly like C, with some exceptions...
- for download and full documentation:
  `http://bricxcc.sourceforge.net/nqc/`
- a smattering of NQC follows
- basic command-line operation:

```
bash# nqc -d <rcx-program-file>
bash# nqc -firmward <firmware-file>
bash# nqc -help
```

- note that the NQC subset presented is for RCX 2.0

(2) NQC: program structure.

- comprised of global variables and code blocks
  - variables are all 16-bit integers
  - code blocks:
    * tasks
    * inline functions
    * subroutines
- features include:
  - event handling
  - resource allocation mechanism
  - IR communication

(2) NQC: tasks.

- multi-tasking program structure

```
task <task-name> {
   // task code goes in here
}
```

- up to 10 tasks
- invoked using `start <task-name>`
- stopped using `stop <task-name>`

(2) NQC: inline functions.

- functions can take arguments but always `void`

```
void <function-name> ( <arguments> ) {
   // function code goes in here
}
```

- `return` statement, just like C
- arguments

type	meaning	description
`int`	pass by value	value can change inside function, but changes won't be seen by caller
`int &`	pass by reference	value can change inside function, and changes will be seen by caller; only variables may be passed
`const int`	pass by value	value cannot be changed inside function; only constants may be passed
`const int &`	pass by reference	value cannot be changed inside function; value is read each time it is used

(2) NQC: subroutines.

- subroutines cannot take any arguments

```
sub <subroutine-name> {
   // subroutine code goes in here
}
```

- allow a single copy of code to be shared by multiple callers
- so more efficient than inline functions
- cannot be nested

(2) NQC: variables.

- all are 16-bit signed integers
- scope is either global or local (just like C)
- use as many local variables as possible (for efficiency)
- arrays
  - declaration just like C
  - cannot pass whole arrays to functions (but can pass individual array elements)
  - cannot use shortcut operators on array elements ($++$, $--$, $+=$, $-=$, etc)
  - cannot do pointer arithmetic
- hexadecimal notation, e.g.: `0x12f`
- special values: `true` (non-zero) and `false` (zero)

(2) NQC: operators.

- operators listed in order of precedence

operator	action
$abs()$ $sign()$	absolute value sign of operand
$++$, $--$	increment, decrement
$-$, ˜, $!$	unary minus, bitwise negation, logical negation
$*$, $/$, $\%$, $+$, $-$	multiply, divide, modulo, addition, subtraction
$<<$, $>>$	left and right shift
$>$, $<$, $>=$, $<=$, $==$, $!=$	relational and equivalence operators
$\&$, $\wedge$, $\vert$	bitwise AND, XOR, OR
$\&\&$, $\vert\vert$	logical AND, OR
$=$ $+=$, $-=$, $*=$, $/=$, $\&=$, $\vert=$	assignment operator shortcut assignment operators
$\vert\vert=$ $+-=$	set variable to absolute value of expression set variable to sign (-1,+1,0) of expression

(2) NQC: preprocessor.

- following directives included:
- `#include "<filename>"`
  - file name must be listed in double quotes (not angle brackets)
- macro definition (`#define`, `#ifdef`, `#ifndef`, `#undef`)[1]
- conditional compilation (`#if`, `#elif`, `#else`, `#endif`)
- program initialization
  - special initialization function (`_init`) called automatically (sets all 3 outputs to full power forward, but not turned on)
  - suppress it using: `#pragma noinit`
  - redirect it using: `#pragma init <function-name>`
- reserving global storage locations (there are 32): `#pragma reserve <value>`

[1] macro redefinition not allowed

(2) NQC: branching statements.

- if / else — just like C

```
if ( <condition> ) <consequence>
if ( <condition> ) <consequence> else <alternative>
```

- switch — just like C

```
switch ( <expression> ) {
  case <constant-expression1> : <body>
  .
  .
  case <constant-expressionN> : <body>
  default : <body>
}
```

(2) NQC: looping statements.

- while, do..while, for — just like C

```
while ( <condition> ) <body>
do <body> while ( <condition> )
for ( <statement0> ; <condition> ; <statement1> ) <body>
```

- also use of `break` and `continue` statements just like C
- repeat loop (not like C):

```
repeat ( <expression> ) <body>
```

  - `<expression>` is evaluated once, indicating the number of times to perform the `body` statements

- until loop (not like C):

```
until ( <condition> );
```

  - effectively a `while` loop with an empty body; program waits until condition is true before proceeding

(2) NQC: resource acquisition.

- `acquire ( <resources> ) <body>`
  `acquire ( <resources> ) <body> catch <handler>`
- resource access control given to task that makes the call
- execution jumps to `catch` handler if access is denied
- note that access can be lost in mid-execution of a task with a higher priority requests the resource; to set task's priority, use `SetPriority( <p> )` where `<p>` is between 0..255; note that lower numbers are higher priority
- resource returned to the system when `<body>` is done
- example:

```
acquire( ACQUIRE_OUT_A ) {
  Wait( 1000 );
}
catch {
  PlaySound( SOUND_UP );
}
```

(2) NQC: event handling.

- ```
  monitor ( <events> ) <body>
  catch ( <catch-events> ) <handler>
  .
  .
  catch <handler>
  ```
- you can configure 16 events, numbered 0..15 and use `EVENT_MASK()` macro to identify

```
monitor( EVENT_MASK(2) | EVENT_MASK(3) | EVENT_MASK(4) ) {
  Wait( 1000 );
}
catch ( EVENT_MASK(4) ) {
  PlaySound( SOUND_DOWN ); // event 4 happened
}
catch {
  PlaySound( SOUND_UP ); // event 2 or 3 happened
}
```
```

(2) NQC: sensors.

- identifiers: SENSOR_1, SENSOR_2, SENSOR_3
- `SetSensorType( <sensor>,<type> )`
  - sets sensor type
  - `<type>` is one of: SENSOR_TYPE_NONE, SENSOR_TYPE_TOUCH, SENSOR_TYPE_TEMPERATURE, SENSOR_TYPE_LIGHT or SENSOR_TYPE_ROTATION
- `SetSensorMode( <sensor>,<mode> )`
  - sets sensor mode
  - `<mode>` is one of: SENSOR_MODE_RAW, SENSOR_MODE_BOOL, SENSOR_MODE_PERCENT, SENSOR_TYPE_LIGHT or SENSOR_TYPE_ROTATION
- `SensorValue( <sensor> )`
  - reads sensor value

(2) NQC: outputs.

- identifiers: OUT_A, OUT_B, OUT_C
- SetOutput(<outputs>,<mode>)
  - sets output mode
  - <mode> is one of: OUT_OFF, OUT_ON or OUT_FLOAT
- SetDirection(<outputs>,<direction>)
  - sets output direction
  - <direction> is one of: OUT_FWD, OUT_REV or OUT_TOGGLE
- SetPower(<outputs>,<power>)
  - sets output power (speed)
  - <power> is one of: OUT_LOW, OUT_HALF, OUT_FULL or 0..7 (lowest..highest)
- multiple <output> identifiers can be added together
- also: On(<outputs>), Off(<outputs>), Fwd(<outputs>), Rev(<outputs>), OnFwd(<outputs>), OnRev(<outputs>), OnFor(<outputs>,<time>) (where <time> is in 100ths of a second)

(2) NQC: sound.

- `PlaySound( <sound> )`
  - plays a sound
  - `<sound>` is one of: `SOUND_CLICK`, `SOUND_DOUBLE_BEEP`, `SOUND_DOWN`, `SOUND_UP`, `SOUND_LOW_BEEP` or `SOUND_FAST_UP`
- `PlayTone( <frequency>, <time> )`
  - plays "music"
  - `<frequency>` is in Hz
  - `<time>` is in 100ths of a second
  - for example:
    `PlayTone( 440, 100 )`

(2) NQC: LCD display.

- `SelectDisplay( <mode> )`
  - displays sensor values
  - `<mode>` is one of: `DISPLAY_WATCH`, `DISPLAY_SENSOR_1`, `DISPLAY_SENSOR_2`, `DISPLAY_SENSOR_3`, `DISPLAY_OUT_A`, `DISPLAY_OUT_B` or `DISPLAY_OUT_C`
- `SetUserDisplay( <value>,<precision> )`
  - displays user values
  - `<value>` is the value to display
  - `<precision>` is the number of places to the right of the decimal point (?!)

(2) NQC: IR communication.

- simple communication can send single (one-byte) messages with values between 0..255
- `x = Message()`
  - reads and returns the most recently received message
- `ClearMessage()`
  - clears the message buffer
- `SendMessage( <message> )`
  - sends a message
  - `<message>` is a value between 0..255

(2) NQC: serial IR communication.

- serial communication allows up to 16-byte messages
- for example:

```
SetSerialComm( SERIAL_COMM_DEFAULT );
SetSerialPacket( SERIAL_PACKET_DEFAULT );
SetSerialData( 0, 10 );
SetSerialData( 1, 25 );
SendSerial( 0, 2 );
```

- `SetSerialData( <byte-number>,<value> )`
  - puts data in one byte of the 16-byte transmit buffer
  - `<byte-number>` is between 0..15
- `SendSerial( <start-byte>,<number-of-bytes> )`
  - sends all or part of the transmit buffer
  - `<start-byte>` is between 0..15
  - `<number-of-bytes>` is between 1..16

(2) NQC: timers.

- allows setting/getting of timers with 100th of a second resolution (fast mode) or 10th of a second resolution (default)
- 4 timers, numbered 0..3
- ClearTimer(<n>)
  - clears specified timer
  - <n> is between 0..3
- x = Timer(<n>)
  - returns the value of specified timer (for default resolution)
- x = FastTimer(<n>)
  - returns the value of specified timer (for 100th of a second resolution)
- SetTimer(<n>,<value>)
  - sets specified timer
  - <value> can be any constant or expression

(2) NQC: counters.

- 3 counters, numbered 0..2[2]
- `ClearCounter( <n> )`
  - clears specified counter
- `IncCounter( <n> )`
  - increments specified counter
- `DecCounter( <n> )`
  - decrements specified counter
- `x = Counter( <n> )`
  - gets the value of specified counter

[2] note that these overlap with global storage locations so these should be reserved if they are going to be used; see `#pragma reserve` description

(2) NQC: event handling.

- allows up to 16 events
- `SetEvent( <event>,<source>,<type> )`
  - configures an event
  - `<event>` is between 0..15
  - `<source>` is the source of the event (e.g., `SENSOR_1`)
  - `<type>` is one of[3]: `EVENT_TYPE_PRESSED`, `EVENT_TYPE_RELEASED`, `EVENT_TYPE_PULSE` (indicates a toggle), `EVENT_TYPE_EDGE`, `EVENT_TYPE_LOW` (use `SetLowerLimit()` to set threshold), `EVENT_TYPE_HIGH` (use `SetUpperLimit()` to set threshold), `EVENT_TYPE_NORMAL`, `EVENT_TYPE_MESSAGE`
- `ClearEvent( <event> )`
  - clears configuration

[3] a subset is shown

(2) NQC: data logging.

- `CreateDatalog( <size> )`
  - creates a data log for recording sensor readings, variable values and the system watch
  - `<size>` is the number of points to record; 0 clears the data log
- `AddToDatalog( <value> )`
  - adds a value to the data log
- `UploadDatalog( <start>,<count> )`
  - uploads the contents of the data log
- to upload and print the content of the data log to the computer from the command-line:

```
bash# nqc -datalog
bash# nqc -datalog_full
```

(2) NQC: miscellaneous functions

- `Wait( <time> )`
  - to sleep
  - `<time>` is a value in 100ths of a second
- `SetRandomSeed( <n> )`
  `x = Random( <n> )`
  - sets random number seed and generates/returns random number between 0..`<n>`
- `SelectProgram( <n> )`
  - sets the current program
  - `<n>` is between 0..4
- `x = Program()`
  - gets currently selected program
- `x = BatteryLevel()`
  - monitors the battery and returns the battery level in millivolts

- `SetWatch( <hours>,<minutes> )`
  - sets system clock
  - `<hours>` is between 0..23
  - `<minutes>` is between 0..59
- `x = Watch()`
  - gets value of system clock in minutes