C# 3.0 and 4.0 new features

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and

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Outline

- C# versions and standards
- New language features
  - Inferred variable types
  - Lambda expressions
  - Extension methods
  - Implicitly typed array creation
  - Anonymous object creation, anonymous types
  - Object initializers, collection initializers
- Linq: Language integrated query
  - On enumerables
  - On relational data
  - Support: Expression trees
- Named arguments and optional parameters
- Dynamically typed expressions
- Co-variant and contra-variant type parameters
- Task Parallel Library

C# and .NET versions

- .NET platform
  - Languages C#, VB.NET, JScript.NET, F#, …
  - Class libraries
  - Bytecode and runtime system CLR
  - Development environment Visual Studio
- 2001: C# 1.0 and .NET 1.0
- 2003: C# 1.1 and .NET 1.1
- 2005: C# 2.0 and .NET 2.0
- 2006: .NET 3.0 (new: WPF, WCF, WF)
- 2007: C# 3.0 and .NET 3.5 a
- 2010: C# 4.0 and .NET 4.0 a

New bytecode and runtime

2.0 bytecode and runtime

Linq drove C# 2.0 -> 3.0 evolution

- The goal of C# 3.0 is to support a type-safe embedded query language
- Previous experimental languages Xen and Cω by Erik Meijer and others
- Based on Haskell comprehensions and Kleisli query language (Buneman 1993)
- Linq is a uniform query language for collections, XML, relational databases
- Design by Hejlsberg, Meijer, Torgersen, ...
- Since July'08 Mono also implements C# 3.0
- Since Oct'10 Mono also implements C# 4.0

Inferred local variable types

- Initialized variable declaration may omit type

```
var h = 3;                    // Inferred: int
var z = 3*2.0;                // Inferred: double
var y = h>2 ? h : z;          // Inferred: double
var a = new double[] { h, 17 };   // double[]
var dict = new Dictionary<int,String>();
```

- Very useful to avoid repetition:

```
Dictionary<int,String> dict
  = new Dictionary<int,String>();
```

- Still static typing, **not** dynamic typing:

```
var x = 3;
x = "foo";    // NO! Rejected by compiler
```


Inferred types in other statements

```
foreach (var x in ...) ...
```

```
for (var x = ...; ...; ...) ...
```

```
using (var x = ...) ...
```

- **No** type inference for
  - Fields of classes and structs
  - Method parameters
  - Method return type
  - Exception variables, as in `catch (MyExn e) ...`
  - Const declarations, as in `const var y = 21;`

Anonymous functions (lambdas)

- New anonymous method (delegate) syntax:

```
delegate (int x) { return x%2==0; }
```

```
(int x) => x%2==0
```

Same meaning

```
x => x%2==0
```

Type inferred

.NET generic delegate types

.NET 3.5 (2007)	C5 library (2004)	Standard ML (1978)
`Action`	`Act`	`unit -> unit`
`Action<A1>`	`Act<A1>`	`A1 -> unit`
`Action<A1,A2>`	`Act<A1,A2>`	`A1*A2 -> unit`
`...`	`...`	`...`
`Func<R>`	`Fun<R>`	`unit -> R`
`Func<A1,R>`	`Fun<A1,R>`	`A1 -> R`
`Func<A1,A2,R>`	`Fun<A1,A2,R>`	`A1*A2 -> R`
`...`	`...`	`...`

worst? ⟷ best?

A little functional programming

- A method to compose a function with itself

```
public static Func<T,T> Twice<T>(Func<T,T> f) {
  return x => f(f(x));
}
```

- Some lambdas and computed functions

```
var fun1 = Twice<int>(x => 3*x);
Func<int,int> triple = x => 3*x;
var fun2 = Twice(triple);
Func<Func<int,int>, Func<int,int>> twice
                      = f => x => f(f(x));
var fun3 = twice(triple);
var res = fun1(4) + fun2(5) + fun3(6);
```


Type system strangeness 1

- Cannot infer type of anonymous function
  - Essentially, most general type is not expressible

```
var triple = x => 3*x;
```

NO: type of x?

```
var twice = f => x => f(f(x));
```

NO

- But type inference from arguments

```
static Func<T,T> Twice<T>(Func<T,T> f) { ... }
Twice(delegate(int x) { return 3*x; })
```

The delegate is used to infer **T=int** in **Twice<T>**, wasn't so in C#2.0

Extension methods

- Can be "added" to any existing type
- Are defined separately in a static class

```
static class BoolExtensions {
  public static void Print(this bool b) {
    Console.WriteLine(b ? "ja" : "nej");
  }
}
```

- Are called like instance methods

```
(1==1).Print();
```


Extension methods as syntactic sugar

- A call to an extension method

```
public static void M(this C x, int y) { ... }

o.M(42)
```

is just a static call with receiver as first arg:

```
M(o, 42)
```

- **Not** the same as an instance method call
- Especially not on struct types

Week numbers (1-53) on DateTime

- Let's teach .NET about ISO week numbers

```
static class DateTimeExtensions {
  public static int IsoWeek(this DateTime dt) {
    int yday=dt.DayOfYear-1, wday=IsoWeekDay(dt), y=dt.Year;
    const int THU = 3;
    ... 10 lines of code omitted ...
  }
}
```

- Use it like any System.DateTime method:

```
int thisWeek = DateTime.Today.IsoWeek();
```


More DateTime extension methods

- Create sequence of dates a week apart

```
public static IEnumerable<DateTime>
   Weekly(this DateTime dt, int n)
{
  for (int added=0; added<n; added++)
    yield return dt.AddDays(added*7);
}
```

```
foreach (var dt in DateTime.Today.Weekly(52))
  Console.WriteLine(dt.ToShortDateString());
```

```
2008-08-13
2008-08-20
2008-08-27
...
```

Extension method on type instance

- A useful function on String arrays

```
static class StringArrayExtensions {
  public static String ConcatWith(this String[] arr, String sep)
    StringBuilder sb = new StringBuilder();
    if (arr.Length > 0)
      sb.Append(arr[0]);
    for (int i=1; i<arr.Length; i++)
      sb.Append(sep).Append(arr[i]);
    return sb.ToString();
  }
}
```

- Call it like it was part of the .NET classes:

```
String[] sarr = { "www", "edlund", "dk" };
sarr.ConcatWith(".")
```

value "www.edlund.dk"

Extension method on generic type

- E.g. define method on Func<A,A> for any A
- The *method* must be generic:

```
static class FuncExtensions {
  public static Func<A,A> Twice<A>(this Func<A,A> f) {
    return x => f(f(x));
  }
}
```

```
Func<int,int> triple = x => 3*x;
int res = triple.Twice()(7);
```

Extension methods on interfaces

```
public static int MyCount<T>(this IEnumerable<T> xs) {
  int count = 0;
  foreach (T x in xs)
    count++;
  return count;
}
```

- Can be used on all implementing types

```
double[] darr = { 4.5, 1.6, 5.6, 7.9 };
Console.WriteLine(darr.MyCount());
List<int> list = ...
Console.WriteLine(list.MyCount());
```

- Lots of extension mths on IEnumerable<T>

... and with type parameter constraint

```
public static bool IsSorted<T>(this IEnumerable<T> xs)
   where T : IComparable<T>
  {
   var etor = xs.GetEnumerator();
   if (etor.MoveNext()) {
     T prev = etor.Current;
     while (etor.MoveNext())
      if (prev.CompareTo(etor.Current) > 0)
        return false;
      else
        prev = etor.Current;
   }
   return true;
  }
```

Only for data that have CompareTo()

```
double[] darr = { 4.5, 1.6, 5.6, 7.9 };
Console.WriteLine(darr.IsSorted());
```

Extension method subtleties 1

- An extension method is non-virtual
- So cannot be used to override `Object.ToString()` which is virtual:

```
static class StringArrayExtensions {
  public static String ToString(this String[] arr) {
    ...
  }
}
```

Legal but useless

- No "extension properties"
- No "extension indexers"

Extension method subtleties 2

- An instance call on a struct passes the struct *by reference*, so its fields can be updated
- An extension method call passes it by value
- So extension method **is not** an instance mth

```
struct MyStruct {
  internal int x;
  public void RealIncrement() {
    x++;
  }
}
static class MyStructExtensions {
  public static void UselessIncrement(this MyStruct b) {
    b.x++;
  }
}
b.UselessIncrement();
```

By value: Pass a *copy* of struct

No effect on b.x

Controlling extension method scope

- Declare extension methods in a namespace

```
namespace MyExtensions {
  public static class MyExtensionsClass {
    public static void MyMethod(this My my) {…}
  }
}
```

- Use namespaces and **using** to control scope

```
namespace N1 {
  using MyExtensions;
  // My.MyMethod usable here
}
namespace N2 {
  // My.MyMethod not usable here
}
```

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A very applicable extension method

- Be careful what extension methods you get in scope from a "foreign" namespace
- Be careful what classes have extension mths

Defined on all types

```
public static class ObjectExtensions {
  public static void toString(this Object receiver,
                              params Object[] args)
  {
    Console.WriteLine("ToString, idiot!");
  }
}
```

Matches all toString signatures

Anonymous object creation

- An anonymous object has named fields

```
double z = 3.14;
var p1 = new { x = 13, y = "foo" };
var p2 = new { x = 42, p1.y, z };
var p3 = new { };
```

- The "field" is a readonly property
- Field name is given or *inferred*: y, z above
- Anon. objects compare and display neatly:

```
{ x = 42, y = foo, z = 3.14 }
```

- Like SML record `{ x=42, y="foo", z=3.14 }`

Type system strangeness 2

- Anon object expressions have same type **iff** same fields of same type in same order
- But the type cannot be expressed in C#
  - Hence anon obj useful only due to type inference
- Only conversion to Object, not any interface
  - So useless for a method to return anonymous obj

```
Object ReturnAnonymousObject() {
  return new { x=4, y=5 };
}
```

Legal but useless

Typing by example (Tomas Petricek)

- Use type param to represent anon type

```
T AnonymousHack<T>(T dummy) {
  return (T)(object)(new { x=4, y=5 });
}
```

- Pass a dummy value of the appropriate type

```
var res = AnonymousHack(new {x=0,y=0});
Console.WriteLine(res.x+1);
```

Type inference binds T to anon type …

… so res is known to have field x of type int

Implicitly typed array creation

- Small type system improvement
- Can write

```
var arr1 = new[] { 4, 3.14 };
```

- Instead of

```
var arr1 = new double[] { 4, 3.14 };
```

- Infers "best common type" for array elems
- Essential for arrays of anonymous objects

```
var arr2 = new[] { new { x=3, y=4 },
                   new { x=6, y=7 } };
foreach (var r in arr2) ... r.x ...
```

Field with automatic properties

- Declares field plus get and set properties

```
class Account {
  public decimal Balance { get; set; }
}
```

Property access

Property access

```
Account acc = ...;
acc.Balance = 23000M;
Console.WriteLine(acc.Balance);
```

- Can change class without breaking clients
- Can restrict accessibility individually:

```
class Account {
  public decimal Balance { get; private set; }
}
```


Object initializer

- New syntax for creation+initialization
- Works for accessible fields and properties

```
struct Point {
  private int _x;
  internal int Y;
  internal int X { get { return _x; }
                   set { _x = value; } }
}
```

```
Point p = new Point { X = 4, Y = 5 };
```

```
Point p = new Point();
p.X = 4;
p.Y = 5;
```

Same meaning

Collection initializer

- Compiles to `Add(…)` method calls
- So work on third-party collections (C5) too
- Overloading resolution works as usual

```
var list2 = new List<int>
            { { 2 }, { 3 }, { 2+3 }, { 5+2 } };
```

```
var list2 = new List<int>();
list2.Add(2);
list2.Add(3);
list2.Add(2+3);
list2.Add(5+2);
```

Same meaning

Simpler syntax sometimes usable

```
var list1 = new List<int> { 2, 3, 2+3, 5+2 };
```


Linq, language integrated query

- Linq in C#:

```
from x in primes where x*x < 100 select 3*x
```

- Set comprehensions, ZF notation:

$$\{ 3x \mid x \in primes, x^2 < 100 \}$$

transformer "select"

generator "from"

filter "where"

- List comprehensions Miranda (1985), Haskell

  [3*x | x <- primes, x*x < 100]

From queries to method calls

- A query such as

```
from x in primes where x*x < 100 select 3*x
```

is transformed to an ordinary C# expression:

```
primes.Where(x => x*x < 100)
      .Select(x => 3 * x)
```

- Only this expression gets type checked
- Where and Select may be extension methods

Basic extension methods for Linq

```
IEnumerable<T> Where<T>(this IEnumerable<T> xs,
                        Func<T,bool> p)
```

- As list comprehension:
  [x | x <- xs, p(x)]

Filter

```
IEnumerable<U> Select<T,U>(this IEnumerable<T> xs,
                           Func<T,U> f)
```

- As list comprehension:
  [f(x) | x <- xs]

Map

Extension methods on IEnumerable

- SCG.IEnumerable<T> used to be simple:

```
interface IEnumerable<T> {
  IEnumerator<T> GetEnumerator();
}
```

- Now these extension methods + 60 others:

```
bool All<T>(this IEnumerable<T> xs, Func<T,bool> p)
bool Any<T>(this IEnumerable<T> xs, Func<T,bool> p)
bool Contains<T>(this IEnumerable<T> xs, T x)
int Count<T>(this IEnumerable<T> xs)
IEnumerable<T> Distinct(this IEnumerable<T> xs)
T First(this IEnumerable<T> xs)
T Single(this IEnumerable<T> xs)
IEnumerable<T> Union(this IEnumerable<T> xs,
                     IEnumerable<T> ys)
...
```


Extension methods on IEnumerable

- Most support Linq for collections
- But an enumerable is nearly a lazy list, so they also support functional programming
- (Except no caching of computed items)

```
double sum = Enumerable.Range(1, 200)
               .Where(x => x%5!=0 && x%7!=0)
               .Select(x => 1.0/x)
               .Sum();
```

Same

```
double sum =
    (from x in Enumerable.Range(1, 200)
     where x%5!=0 && x%7!=0
     select 1.0/x).Sum();
```

Performance of Linq-style queries

- Query is only 1.7 times slower than this loop

.NET 3.5 SP1

```
double sum = 0.0;
for (int x=1; x<=200; x++)
  if (x%5!=0 && x%7!=0)
    sum += 1.0/x;
```

- For near-trivial loop contents, a factor 11.2:

```
(from x in Enumerable.Range(1, 200)
 where (x & 1) == 0
 select 1 + x).Sum();
```

7031 ns

```
double sum = 0.0;
for (int x=1; x<=200; x++)
if ((x & 1) == 0)
   sum += 1 + x;
```

625 ns

The form of a query expression 1

```
from x in xs
query-body-clauses
select e
```

```
from x in xs
query-body-clauses
group e by e
```

query-body-clauses

```
from y in ys
let x = e
where b
join y in ys on e1 equals e2
join y in ys on e1 equals e2 into z
orderby e1, e2, ...
```

The form of a query expression 2

- A query can have continuations, of form:

```
...
into z
query-body-clauses
select e
```

```
...
into z
query-body-clauses
group e by e
```


Some differences from SQL

- No DISTINCT in select, instead
  (from … select …).Distinct()
- UNION, INTERSECT, EXCEPT done like this
  (from … select …).Union(from … select …)
- No HAVING, instead
  … group … into g where … g …
- COUNT done like this
  (from … select …).Count()
- SUM, AVG, MIN, MAX done like this
  (from … select …).Sum()
  - These work on a few numerical and nullable numerical types; MIN, MAX also on ordered types

What do they collect this week?

- Even weeks: garden waste; odd: recycling
- Friday (e.g. 15 Aug 2008), except holidays

```
var collect =
  from dt in new DateTime(2008, 8, 15).Weekly(520)
  where !dt.IsHoliday()
  select new { dt, art=dt.IsoWeek()%2==0 ? "Haveaffald"
                                         : "Storskrald" };
foreach (var x in collect)
  Console.WriteLine(x);
```

- May have two odd weeks (53 and 1) in a row

When are two weeks in a row odd?

```
var gentagelse =
  from dt in new DateTime(2010, 1, 29).Weekly(5200)
  let dtNext = dt.AddDays(7)
  where (dt.IsoWeek()%2==0) == (dtNext.IsoWeek()%2==0)
  select new { dt, dtNext };
foreach (var x in gentagelse)
  Console.WriteLine(x);
```

- Uses the let-clause
  - Normally used to avoid repeated computation
  - E.g. using result of aggregate in further query:

```
var categories =
  from p in products
  group p by p.Category
  into g
  let min = g.Min(p => p.UnitPrice)
  select new {Category = g.Key,
              Cheapest = g.Where(p => p.Price == min)};
```

Translation of let

- The query

```
from x in xs
let y = f ...
```

is expanded to

```
from * in (xs.Select(x => new { x, y=f }))
```

New sequence of pairs (x,y)

Weekday distribution of holidays

```
var holidayWeekDays =
  from dt in DateTimeExtensions.holidays.Keys
  group dt by dt.DayOfWeek
  into g
  select new { g.Key, Count = g.Count() };
```

```
{ Key = Tuesday, Count = 15 }
{ Key = Sunday, Count = 95 }
{ Key = Thursday, Count = 60 }
{ Key = Friday, Count = 61 }
{ Key = Monday, Count = 52 }
{ Key = Wednesday, Count = 17 }
{ Key = Saturday, Count = 18 }
```

Translation of group by

- The query

```
from x in xs group x by e
```

is expanded to

```
xs.GroupBy(x => e)
```

- The query

```
from x in xs group x.Name by x.Age
```

is expanded to

```
xs.GroupBy(x => x.Name, x => x.Age)
```


Extension methods for grouping

```
IEnumerable<IGrouping<K,T>>
      GroupBy<T,K>(this IEnumerable<T> xs, Func<T,K> h)
```

- As list comprehension
  - Compute ks = distinct([h(x) | x <- xs])
  - Return [(k, [x | x <- xs, h(x)=k]) | k <- ks]
- A grouping is an enumerable with a key:

```
interface IGrouping<K,T> : IEnumerable<T> {
  K Key { get; }
}
```

- There are several additional overloads

Translations of join

- The query

```
from x in xs
join y in ys on kx equals ky
select e
```

is expanded to

```
xs.Join(ys, x => kx, y => ky, (x,y) => e)
```

- The query

```
from x in xs
join y in ys on kx equals ky into z
select e
```

is expanded to

```
xs.GroupJoin(ys, x => kx, y => ky, (x,z) => e)
```


Extension methods for join 1

```
IEnumerable<V> Join<T,U,K,V>(this IEnumerable<T> xs,
                             IEnumerable<U> ys,
                             Func<T,K> fx,
                             Func<U,K> fy,
                             Func<T,U,V> g)
```

- As list comprehension:
  [g(x,y) | x <- xs, y <- ys, fx(x)=fy(y)]

- Efficient even on enumerables (I guess):
  - Make multidictionary fx(x) -> x for all x in xs
  - For each y in ys compute fy(y), look up matching x values, for each of them yield g(x,y)

Extension methods for join 2

```
IEnumerable<V> GroupJoin<T,U,K,V>
    (this IEnumerable<T> xs,
     IEnumerable<U> ys,
     Func<T,K> fx,
     Func<U,K> fy,
     Func<T,IEnumerable<U>,V> g)
```

- As list comprehension:
  [g(x, [y | y <- ys, fx(x)=fy(y)]) | x <- xs]

Order weekday distribution by weekday

```
var holidayWeekDays =
  from dt in DateTimeExtensions.holidays.Keys
  group dt by dt.DayOfWeek
  into g
  orderby g.Key
  select new { g.Key, Count = g.Count() };
```

```
{ Key = Sunday, Count = 95 }
{ Key = Monday, Count = 52 }
{ Key = Tuesday, Count = 15 }
{ Key = Wednesday, Count = 17 }
{ Key = Thursday, Count = 60 }
{ Key = Friday, Count = 61 }
{ Key = Saturday, Count = 18 }
```

Translation of orderby

- The query

```
from x in xs
orderby k1, k2, ...
```

is expanded to

```
xs.OrderBy(x => k1)
   .ThenBy(x => k2)
   . ...
```


Extension methods for ordering

```
IOrderedEnumerable<T>
   OrderBy<T,K>(this IEnumerable<T> xs, Func<T,K> h)
```

- Order xs by ascending h(x)

- An ordered enumerable
  - remembers its previous ordering criteria
  - supports ordering by further (secondary) criteria while respecting previous criteria

```
IOrderedEnumerable<T>
  ThenBy<K>(this IOrderedEnumerable<T> xs, Func<T,K> h)
```

Query execution

- The IEnumerable extension methods are lazy
- So a query is executed only when – and every time – the result is demanded:

```
int[] numbers = new int[] { 5, 4, 1, 3, 9 };
int j = 0;
var q = from n in numbers select new { n, i = ++j };
foreach (var v in q)
  Console.WriteLine(v);
foreach (var v in q)
  Console.WriteLine(v);
```

```
{ n = 5, i = 1 }
{ n = 4, i = 2 }
{ n = 1, i = 3 }
{ n = 3, i = 4 }
{ n = 9, i = 5 }
{ n = 5, i = 6 }
{ n = 4, i = 7 }
{ n = 1, i = 8 }
{ n = 3, i = 9 }
{ n = 9, i = 10 }
```

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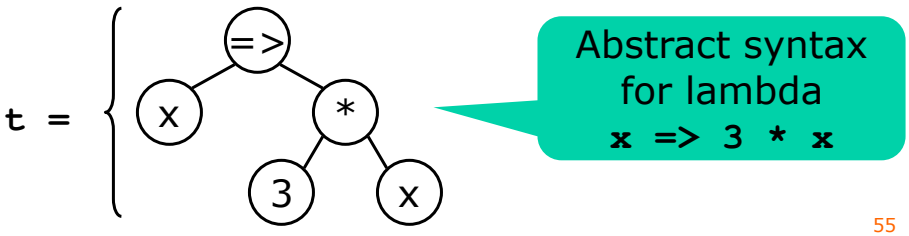
Expression trees

- A reflective representation of expressions
- Covers C# expressions except assignment
- A function can be called but not inspected:

```
Func<int,int> f = x => 3*x;
int res = f(7);
```

- An expression tree can be inspected:

```
Expression<Func<int,int>> t = x => 3*x;
```



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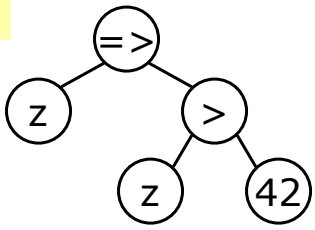
From lambda to expression tree

- A lambda may convert to expression tree at assignment to variable, field or parameter

```
bool Where(Expression<Func<int,bool>> p) {…}
```

```
bool foo = Where(z => z>42);
```



- p will be a tree, not a function
- The tree may be analysed by the Where method

Linq to relational databases

- For Linq to collections (or in-memory XML), enumerable extension methods are efficient
- For Linq to relational database, they aren't
- Instead,
  - the query gets rewritten to method calls, as usual
  - the `System.Linq.Data.Table.Where` method is `Where(Expression<Func<T,bool>> p)`
  - it captures the predicate p as an expression tree and rewrites it to an SQL fragment
  - same for Select, Join, GroupBy, OrderBy, ThenBy
  - the DB server executes SQL and returns results
- Works even if the delegates involve local (client-side) computation, but may be slow

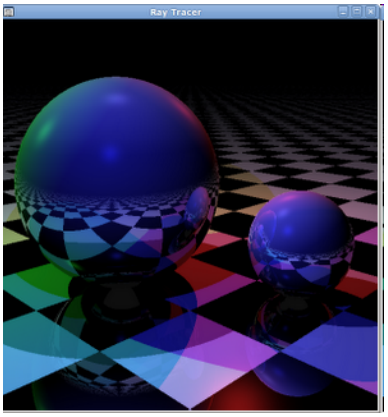
Linq samples in VS2010

- Go **`Help > Samples > CSharpSamples > LinqSamples > SampleQueries`**
- Build and run project SampleQueries
- Shows the SQL generated by Linq to SQL
- See *101+ Linq to Sql Query Samples*

- If not installed, then first
  - go **`Help > Samples > local Samples folder > unzip CSharpSamples.zip`**
  - install in **`Program Files\Microsoft Visual Studio 10.0\Samples\1033\CSharpSamples\`**

Weird uses of Linq

- Ray tracer in one Linq statement by Luke Hoban (now F# program manager)
- Links from Miguel de Icaza's blog http://tirania.org/blog/archive/2008/Jul-26-1.html



```
var pixelsQuery =
  from y in Enumerable.Range(0, screenHeight)
  let recenterY = -(y - (screenHeight / 2.0)) / (2.0 * screenHeight)
  select from x in Enumerable.Range(0, screenWidth)
       let recenterX = (x - (screenWidth / 2.0)) / (2.0 * screenWidth)
       let point = Vector.Norm(Vector.Plus(scene.Camera.Forward,
                          Vector.Plus(Vector.Times(recenterX, scene.Camera.Right),
                                 Vector.Times(recenterY, scene.Camera.Up))))
       let ray = new Ray { Start = scene.Camera.Pos, Dir = point }
       let computeTraceRay = (Func<Func<TraceRayArgs, Color>, Func<TraceRayArgs, Color>>)
      (f => traceRayArgs =>
       (from isect in
          from thing in traceRayArgs.Scene.Things
          select thing.Intersect(traceRayArgs.Ray)
        where isect != null
        orderby isect.Dist
        let d = isect.Ray.Dir
        let pos = Vector.Plus(Vector.Times(isect.Dist, isect.Ray.Dir), isect.Ray.Start)
        let normal = isect.Thing.Normal(pos)
        let reflectDir = Vector.Minus(d, Vector.Times(2 * Vector.Dot(normal, d), normal))
        let naturalColors =
          from light in traceRayArgs.Scene.Lights
          let ldis = Vector.Minus(light.Pos, pos)
          let livec = Vector.Norm(ldis)
          let testRay = new Ray { Start = pos, Dir = livec }
          let testIsects = from inter in
                     from thing in traceRayArgs.Scene.Things
                     select thing.Intersect(testRay)
                   where inter != null
                   orderby inter.Dist
                   select inter
          let testIsect = testIsects.FirstOrDefault()
          let neatIsect = testIsect == null ? 0 : testIsect.Dist
          let isInShadow = !((neatIsect > Vector.Mag(ldis)) || (neatIsect == 0))
          where !isInShadow
          let illum = Vector.Dot(livec, normal)
          let lcolor = illum > 0 ? Color.Times(illum, light.Color) : Color.Make(0, 0, 0)
          let specular = Vector.Dot(livec, Vector.Norm(reflectDir))
          let scolor = specular > 0
                 ? Color.Times(Math.Pow(specular, isect.Thing.Surface.Roughness), light.Color)
                 : Color.Make(0, 0, 0)
          select Color.Plus(Color.Times(isect.Thing.Surface.Diffuse(pos), lcolor),
                  Color.Times(isect.Thing.Surface.Specular(pos), scolor))
        let reflectPos = Vector.Plus(pos, Vector.Times(.001, reflectDir))
        let reflectColor =
          traceRayArgs.Depth >= MaxDepth
          ? Color.Make(.5, .5, .5)
          : Color.Times(isect.Thing.Surface.Reflect(reflectPos),
                f(new TraceRayArgs(new Ray { Start = reflectPos, Dir = reflectDir },
                          traceRayArgs.Scene,
                          traceRayArgs.Depth + 1)))
        select naturalColors.Aggregate(reflectColor, (color, natColor) => Color.Plus(color, natColor)))
                 .DefaultIfEmpty(Color.Background).First())
       let traceRay = Y(computeTraceRay)
       select new { X = x, Y = y, Color = traceRay(new TraceRayArgs(ray, scene, 0)) };
```

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Linq-related patent applications

- Data retrieval from a database utilizing efficient eager loading and customized queries. US2008177716
- Syntax for members added through object protocol systems and methods. US2008046456
- A generic interface for deep embedding of expression trees in programming languages. US2007271233
- Generational global name table. US2007061092 (?)
- Query comprehensions. US2007050347
- Lambda expressions. US2007044083
- Integrating query-related operators in a programming language. US2007027849
- Compiler supporting programs as data objects. US2007028223
- Anonymous types for statically typed queries. US2007027862
- Extending expression-based syntax for creating object instances. US2007028212
- Retrieving and persisting objects from/to relational databases. US2007027906
- Intelligent SQL generation for persistent object retrieval. US2007027905
- Free/outer variable capture. US2007028222
- Architecture that extends types using extension methods. US2007028209

Filed 2007-2008, mostly with Anders Hejlsberg and Erik Meijer as inventors.
(Retrieved from ep.espacenet.com on 12 August 2008)

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New in C# 4.0

- Default-value method parameters
- Named method arguments
- Type **`dynamic`**: Run-time resolution of method calls, method overloading, operators
- Co-variance and contra-variance in generic interfaces: **`I<out T>`** and **`I<in T>`**
- Task Parallel Library: simple concurrency

Default-value (optional) parameters

- Parameters may have default values

```
static uint Convert(String s, uint radix = 10) {
  ...
}
```

  – Default value must be compile-time constant

- Default-value arguments may be left out

```
Convert("123");
Convert("123", 10);
Convert("123", 8);
```

- Rules
  – Order: Required; default; parameter array
  – A **`ref`** or **`out`** parameter cannot have default value

Named arguments

- In calls, arguments may be named

```
s.IndexOf("foo", startIndex: 4, count: 3)
s.Replace(oldValue: "foo", newValue: "bar")
```

  – Useful when several arguments have same type
- Named arguments can appear in any order

```
s.IndexOf("foo", count: 3, startIndex: 4)
s.Replace(newValue: "bar", oldValue: "foo")
```

- Works with ref and out too

```
quotrem(7, 3, quot: out q, rem: out r);
```

- Named arguments must come last in call
  – Cannot really be used with parameter arrays

Subtlety: Subtype may rename parameters

```
interface II {
  void M(int xx, int yy);
}
class AA : II {
  public virtual void M(int x, int y) { ... }
}
class BB : AA {
  public override void M(int y, int x) { ... }
}
```

What happens here?

And here?

```
II obj;
obj = new AA();
obj.M(xx: 2, yy: 3);
obj = new BB();
obj.M(xx: 2, yy: 3);
```

Name is resolved by `obj`'s compile-time type: `II`

C# 4.0: Dynamically typed expressions

- Type **dynamic** is a compile-time type
- Contrast with **var**-declared variables

Keyword

```
var x = 29;
x = "Kirkevej";
... x.ToUpper()
```

Compile-time type **int**

Error at compile-time

Type

```
dynamic x = 29;
x = "Kirkevej";
... x.ToUpper()
```

Compile-time type **dynamic**

OK at compile- and run-time

- Type **dynamic** is similar to Object: a value gets boxed and carries its exact type at run-time
- **Moreover**, resolution of methods, operators and overloading happens at run-time

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Using expressions of type dynamic

```
static void TryDynamic(dynamic x) {
  if (x is int)
    Console.WriteLine(x - 10);
  long xLong = x;   // Check and conversion
  x = M();
  Console.WriteLine(x + 10);
  dynamic[] arr = new dynamic[10];
  arr[0] = 19;
  arr[1] = "Electric Avenue";
  arr[2] = x;
  int number = arr[0] * 5;
  String street = arr[1].ToUpper();
}
```

```
static dynamic M() { return 16; }
```

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Using the `dynamic` type

- Can
  - Use as method return type
  - Use as method parameter type, almost same as Object
  - Use as method argument, with overload res. at runtime
  - Use as type parameter in arrays and generic types:

```
dynamic[] arr = new dynamic[10];
List<dynamic> list = new List<dynamic>();
```

  - Cast to **dynamic**:

```
M(obj)   versus   M((dynamic)obj)
((dynamic)("foo".Clone())).ToUpper()
```

- Cannot
  - Use **dynamic** in generic type parameter constraint
  - Use extension methods on dynamic receiver obj.Count()
  - Pass anonymous method to a method with dynamic receiver
- Type rules:
  - An expression with a **dynamic** operand has type **dynamic**

Runtime resolution of `d.M(…)`

- **d** is a COM object
  - Resolves call at runtime through COM IDispatch
- **d** implements .NET interface IDynamicObject
  - Class of d determines how calls are resolved
  - More …
- **d** is any other .NET object (or boxed value)
  - At runtime it will be checked whether d supports the operation, and if so it will be invoked
  - Method overloading is resolved at runtime

- NO change to the .NET runtime system
- But new API, Dynamic Language Runtime

Implementation of dynamic overloading

- Example class

```
class TestDynamicImplementation {
  public static void Main() {
    dynamic x;
    x = "foo";
    int res = MyMethod(x);
    Console.WriteLine(res);
  }

  static int MyMethod(int x) { return x * x; }
  static int MyMethod(String s) { return s.Length; }
}
```

How to do this?

- Compiled to ordinary .NET bytecode
- Using the Dynamic Language Runtime API


```
.class TestDynamicImplementation {
  .class abstract sealed nested private '<Main>o__SiteContainer0' {
    .field static CallSite`1<Func`3<CallSite,object,int32>> '<>p__Site1'
    .field static CallSite`1<Func`4<CallSite,Type,object,object>> '<>p__Site2'
  }
  .method public hidebysig static void  Main() cil managed {
    .locals init (object V_0,
                  int32 V_1,
                  class CSharpArgumentInfo[] V_2)
    IL_0000:  ldstr      "foo"
    IL_0005:  stloc.0
    IL_0006:  ldsfld     '<Main>o__SiteContainer0'::'<>p__Site1'
    IL_000b:  brtrue.s   IL_0027

    IL_000d:  ldc.i4.0
    IL_000e:  ldtoken    [mscorlib]System.Int32
    IL_0013:  call       Type::GetTypeFromHandle(RuntimeTypeHandle)
    ...
    IL_003d:  ldc.i4.0
    IL_003e:  ldstr      "MyMethod"
    ...
    IL_0075:  stsfld     '<Main>o__SiteContainer0'::'<>p__Site2'

    IL_007a:  ldsfld     '<Main>o__SiteContainer0'::'<>p__Site2'
    IL_007f:  ldfld      !0 CallSite`1<Func`4<CallSite,Type,object,object>>::Target
    IL_0084:  ldsfld     '<Main>o__SiteContainer0'::'<>p__Site2'
    IL_0089:  ldtoken    TestDynamicImplementation
    IL_008e:  call       Type::GetTypeFromHandle(RuntimeTypeHandle)
    IL_0093:  ldloc.0
    IL_0094:  callvirt   !3 Func`4<CallSite,Type,object,object>::Invoke(!0, !1, !2)
    IL_0099:  callvirt   !2 Func`3<CallSite,object,int32>::Invoke(!0, !1)
    IL_009e:  stloc.1
    IL_009f:  ldloc.1
    IL_00a0:  call       Console::WriteLine(int32)
    IL_00a5:  ret
  }
```

Nested class inserted

dynamic x;

Initialization of nested class's fields

Calling **MyMethod(x)**

Runtime overhead of `dynamic`

- A value of type dynamic must be boxed, and hence allocated in the heap, not stack
- Safety of **`dynamic`** relies on runtime checks
- Heap allocation and checks take time:

```
double sum = 0.0;
for (int i=count; i>0; i--)
  sum += (1.0 + i) * i;
```

3.2 ns/iter

```
dynamic sum = 0.0;
for (int i=count; i>0; i--)
  sum += (1.0 + i) * i;
```

24.5 ns/iter

- If a method call has a dynamic argument, overload resolution is done at runtime: slow

Feature interaction/corner case: named arguments and dynamic

```
II obj = ...;
obj.M(xx: 2, yy: 3);
```

Arg. names resolved by compile-time type

```
dynamic obj = ...;
obj.M(xx: 2, yy: 3);
```

No compile-time type, ehh??

- Runtime overload resolution seems to …
  - first finds methods with the right number and *names* of parameters
  - next finds the best overload – e.g. **`String`** better than **`Object`** for argument "foo"

Reminder: Generics in C# and Java

- Polymorphic types

```
interface IEnumerable<T> { ... }
class List<T> : IEnumerable<T> { ... }
struct Pair<T,U> { T fst; U snd; ... }
delegate R Func<A,R>(A x);
```

- Polymorphic methods

```
void Process<T>(Action<T> act, T[] xs)
```

C#

```
void <T> Process(Action<T> act, T[] arr)
```

Java

- Type parameter constraints

```
void Sort<T>(T[] arr) where T : IComparable<T>
```

C#

```
void <T extends Comparable<T>> Sort(T[] arr)
```

Java

Invariance in type parameters

- Assume Student is subtype of Person

```
void PrintPeople(IEnumerable<Person> ps) { ... }
```

```
IEnumerable<Student> students = ...;
PrintPeople(students);
```

Java and C# 3 say NO: Ill-typed!

- C# 3 and Java:
  - A generic type is *invariant* in its parameter
  - I<Student> is *not* subtype of I<Person>
- Co-variance (co=with):
  - I<Student> is subtype of I<Person>
- Contra-variance (contra=against):
  - I<Person> is subtype of I<Student>

Co-/contra-variance is unsafe in general

- Co-variance is unsafe in general

```
List<Student> ss = new List<Student>();
List<Person> ps = ss;
ps.Add(new Person(...));
Student s0 = ss[0];
```

Wrong!

Because would allow writing Person to Student list

- Contra-variance is unsafe in general

```
List<Person> ps = ...;
List<Student> ss = ps;
Student s0 = ss[0];
```

Wrong!

Because would allow reading Student from Person list

- But:
  - co-variance OK if we *only read (output)* from list
  - contra-variance OK if we *only write (input)* to list

Co-variance in interfaces, C# 4.0

- When an I<T> only produces/outputs T's, it is safe to use an I<Student> where a I<Person> is expected
- This is *co*-variance
- Co-variance is declared with the `out` modifier

```
interface IEnumerable<out T> {
  IEnumerator<T> GetEnumerator();
}
interface IEnumerator<out T> {
  T Current { get; }
}
```

- Type T can be used only in output position; e.g. not as method argument (input)

Contra-variance in interfaces, C# 4.0

- When an I<T> only consumes/inputs T's, it is safe to use an I<Person> where an I<Student> is expected
- This is *contra*-variance
- Contra-variance is declared with **`in`** modifier

```
interface IComparer<in T> {
  int Compare(T x, T y);
}
```

- Type T can be used only in input position; e.g. not as method return type (output)

Variance in function types, C# 4.0

- A C# delegate type is
  - co-variant in return type (output)
  - contra-variant in parameters types (input)
- Return type co-variance:

```
Func<int,Student> nthStudent = ...
Func<int,Person> nthPerson = nthStudent;
```

- Argument type contra-variance:

```
Func<Person,int> personAge = ...
Func<Student,int> studentAge = personAge;
```

How Java does it: use-side wildcards

- Use-side co-variance

```
void PrintPeople(ArrayList<? extends Person> ps) {
  for (Person p : ps) { … }
}
...
PrintPeople(new ArrayList<Student>());
```

OK!

- Use-side contra-variance

```
void AddStudentToList(ArrayList<? super Student> ss) {
  ss.add(new Student());
}
...
AddStudentToList(new ArrayList<Person>());
```

OK!

Decidability of Java's wildcard types

- It is unknown whether Java typechecking is decidable – so not clear that the compiler will always terminate
- Indeed, some short Java programs cause Sun's Java compiler serious headaches:

```
class T { }
class N<Z> { }
class C<X> extends N<N<? super C<C<X>>>> {
  N<? super C<T>> cast(C<T> c) {
    return c;
  }
}
```

Kennedy & Pierce 2007

The future of C#

- Further ahead
  - Compiler API usable by client code (PDC2010)
  - Software transactional memory?
  - Join patterns (a library by Claudio Russo 2007)?
  - Actors (à la Scala and F#, MSR library 2009)?

"C# will keep growing and some day it may collapse under its own weight"

Anders Hejlsberg
at the IT University 2007
(quoted from memory)

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