How random is Random?

Pitfalls of Random in .NET 6

Stan Drapkin

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Who am I?

Stan Drapkin – sdrapkin@sdprime.com

- Senior Director - Cloud Technologist - EPAM Systems Inc.
- 20 years of .NET experience
- Specialize in .NET, SQL Server, Security, Cryptography, Cloud
- OSS library author – github.com/sdrapkin
- Book author
  - Security Driven .NET (2014)
  - Application Security in .NET, Succinctly (2017)
- Conference speaker

Opinions expressed are my own

Random History 2001~2021

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- A lot of .NET code already relied on reproducible seeded SR values
- It was often bad code, but users don’t like to be told they are the problem

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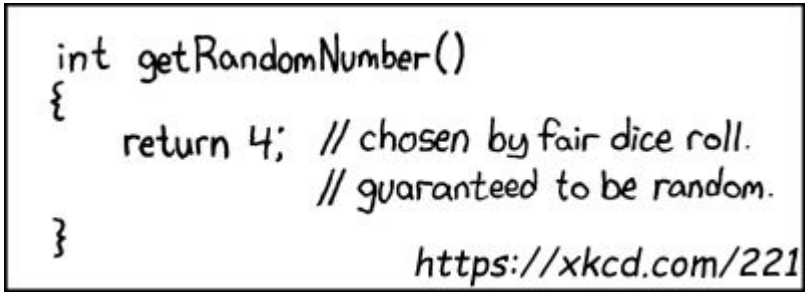
- Stability is a feature: MS chose seeded stability over correctness
- But what’s wrong with existing `System.Random`? **DEMO TIME**

new `System.Random()` for .NET 6 ?

we need an algorithm…

Obligatory – xkcd random



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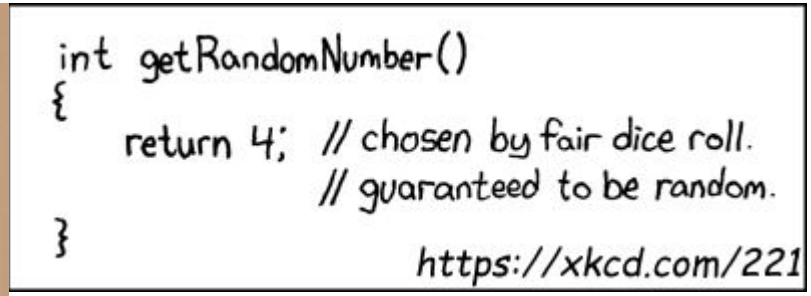

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int getRandomNumber()
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https://xkcd.com/221

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$X_{i+1} = (A * X_i + C) \bmod M \qquad i = 0, 1, 2, \ldots$

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$X_{i+1} = (A * X_i + C) \bmod M$ $\quad i = 0, 1, 2, \ldots$

$X_{i+1} = (1 * X_i + 0) \bmod 5$ $\quad X_0 = 4$

M = modulus	= 5	$(M > 0)$
C = increment	= 0	$(C < M)$
A = multiplier	= 1	$(A < M)$
X_0 = first value	= 4	

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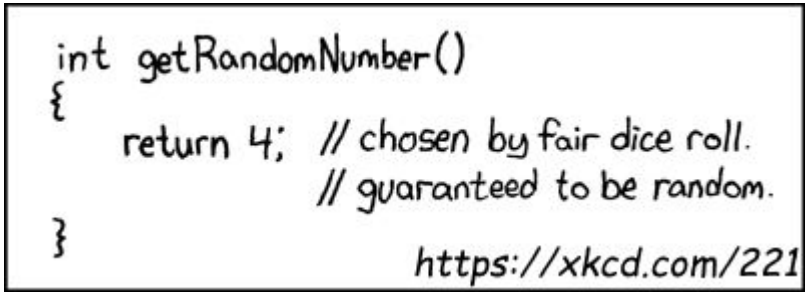
- **Super fast!** (benchmark crashed dividing by 0)
- Vectorization friendly (SSE/AVX/SIMD)
- Tiny 32-bit global state, no per-instance state
- Thread-safe!
- Equidistributed in every dimension, no gaps
- Covers its entire output range
- No run-ups or run-downs
- All output permutations are equally likely
- Precise mathematically-proven period
- Nothing-up-my-sleeve design
- Well implemented & documented
- Consistent on all .NET runtimes and CPU arch.
- Public domain, patent-free (I hope)

What's not to like? It's **very fast**, might be **good enough**...



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`Random()` in .NET 6

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PR #47085, PR #50297 from Stephen Toub, one of key .NET team engineers:

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- Adds:
  - `long NextInt64()` // [0 … long.MaxValue)
  - `long NextInt64(max)` // [0 … max)
  - `long NextInt64(min, max)` // [min … max)
  - `float NextSingle()` // [0.0f … 1.0f)

.NET 6 blog: changes to Random

https://devblogs.microsoft.com/dotnet/performance-improvements-in-net-6/

Stephen Toub, Partner Software Engineer on .NET team:

"...over the years we've been hesitant to change `Random`'s implementation for fear of changing the numerical sequence yielded if someone provided a fixed seed to `Random`'s constructor (which is common); now in .NET 6, just as for derived types, we fall back to the old implementation if a seed is supplied, otherwise preferring the new algorithm. This sets us up for the future where we can freely change and evolve the algorithm used by `new Random()` as better approaches appear."

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Stephen Toub, Partner Software Engineer on .NET team:

“Until .NET 6, Random employed the same algorithm it had been using for the last 2 decades, a variant of Knuth’s alg that dates back to the 1980s. That served .NET well, but it was time for an upgrade. A myriad number of pseudo-random algorithms have emerged, and for .NET 6 we picked the xoshiro** family, using xoshiro128** on 32-bit and xoshiro256** on 64-bit. These algorithms were introduced by Blackman and Vigna in 2018, are **very fast**, and yield **good enough** pseudo-randomness for Random‘s needs.
For cryptographically-secure rng, SSC.RNG should be used instead.”

.NET 6 Github: changes to Random

Dan Moseley, Group Manager for .NET libraries team, on xoshiro256**:

“...it looks like we didn't really do a "survey" of the PRNG options…
Since we aren't implementing a seeded API here, which we can always change later, perhaps that doesn't matter very much so long as we're reasonably confident that it's not "worse" since folks seem to be mostly wanting more performance and asking for more randomness.”

“xoshiro256** implementation is super simple so unless we discover a significant flaw I think we should go ahead and use it and lock in the **sweet perf gain**. Then we can always change later.”

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- xoshiro is made of 2 parts: a Linear Engine (**LE**), and a Scrambler (**SC**)
  - **LE**: cycles through internal state **s**
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    - tries to make output less statistically biased

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- 3 xoshiro Scramblers are defined: +, ++, and **
  - ulong Scrambler_Plus(ulong[] **s**) => **s**[0] + **s**[3];
  - ulong Scrambler_PlusPlus(ulong[] **s**) => Rotl(**s**[0] + **s**[3], 7) + **s**[0];
  - ulong Scrambler_StarStar(ulong[] **s**) => Rotl(**s**[1] * 5, 7) * 9;

What is xoshiro Linear Engine (LE)?

```
void Xoshiro_LE(ulong[] s)        // s is 4-value state; xoshiro256 is shown here
{
        ulong temp = s[1] << 17;  // “17” is a magic constant A
        s[2] ^= s[0];
        s[3] ^= s[1];
        s[1] ^= s[2];
        s[0] ^= s[3];
        s[2] ^= temp;
        s[3] = Rotl(s[3], 45);    // “45” is a magic constant B
}
```

What is xoshiro256** algorithm? LE + Scrambler

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ulong Xoshiro_StarStar(ulong[] s)
{
    ulong next = Scrambler_StarStar(s); // pure fn of current state
    Xoshiro_LE(s); // cycles state
    return next;
}
```

Zeroland

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- Linear generators like `xoshiro` take a long time to escape **Zeroland**
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- Xoshiro escapes **Zeroland** faster than most, but still suffers from it
- Idea #1: randomize state to make **Zeroland** highly unlikely (ex. 256-bit state)
- Idea #2: cycle state a few times after seeding (ex. 16 times) prior to use

Cryptographically Secure rng (csrng)

xoshiro requires randomness to generate randomness: where does it get it?

- System.Security.Cryptography.RandomNumberGenerator.Fill(ulong[] **s**)

Recall this advice?

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4. Cannot recover past output from current state (future output will be known)

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xoshiro is trivially predictable: given only 4 xoshiro outputs, we can:

- Derive all prior outputs
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It's not about "cryptography" – it's about **security** and **correctness**

- Any randomized algorithm with external inputs is potentially vulnerable

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xoshiro-based Random() initializes from RandomNumberGenerator (RNG)

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Perhaps we could fix #1 and #2

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Can we make a randomness-provider wishlist 2021?

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System.Random:
- Convenient API
- High Performance

SSC.RNG:
- Superior Randomness
- Thread Safety

CryptoRandom – modern replacement for Random & RNG

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Is it fast enough?

- byte throughput
- call throughput

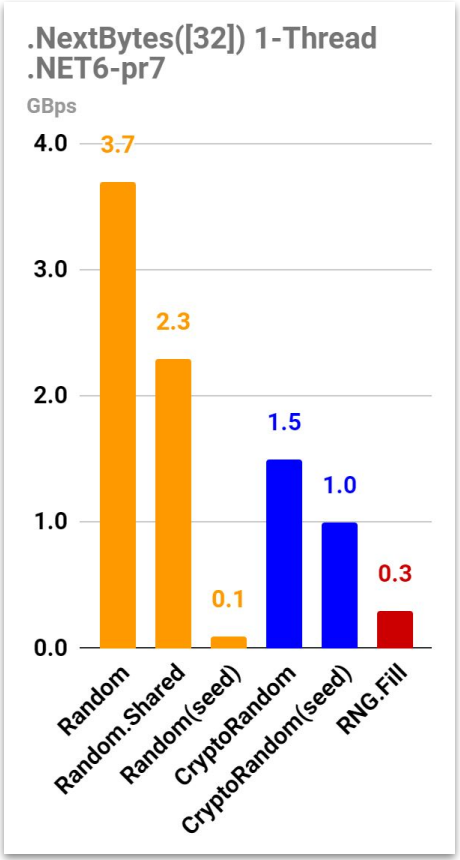
…but what is “fast enough”?

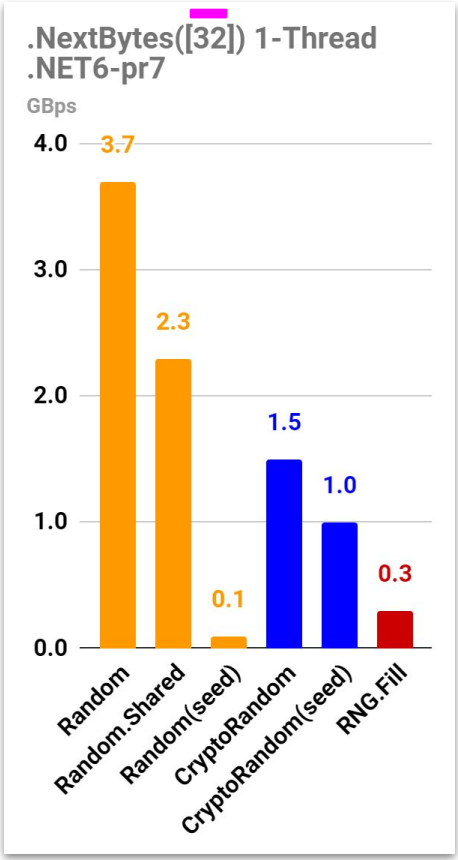
- Fastest Local Devices 2021:
  - Thunderbolt 3: ~5.0 GBps
  - USB 3.2: ~2.0 GBps
  - 10G Ethernet: ~1.2 GBps
  - 25G Ethernet: ~3.1 GBps
  - Fastest SSD drives: ~3.1 GBps (https://ssd.userbenchmark.com/)

…but what is “fast enough”?

- Fastest Local Devices 2021:
  - Thunderbolt 3: ~5.0 GBps
  - USB 3.2: ~2.0 GBps
  - 10G Ethernet: ~1.2 GBps
  - 25G Ethernet: ~3.1 GBps
  - Fastest SSD drives: ~3.1 GBps (https://ssd.userbenchmark.com/)

- Fastest durable Cloud Storage 2021:
  - Alibaba ~4.0 GBps
  - Azure: ~2.0 GBps
  - AWS: ~4.0 GBps
  - GCP: ~2.2 GBps


.NextBytes([32]) 1-Thread
.NET6-pr7
GBps
4.0
3.0
2.0
1.0
0.0
3.7
2.3
0.1
1.5
1.0
0.3
Random
Random.Shared
Random(seed)
CryptoRandom
CryptoRandom(seed)
RNG.Fill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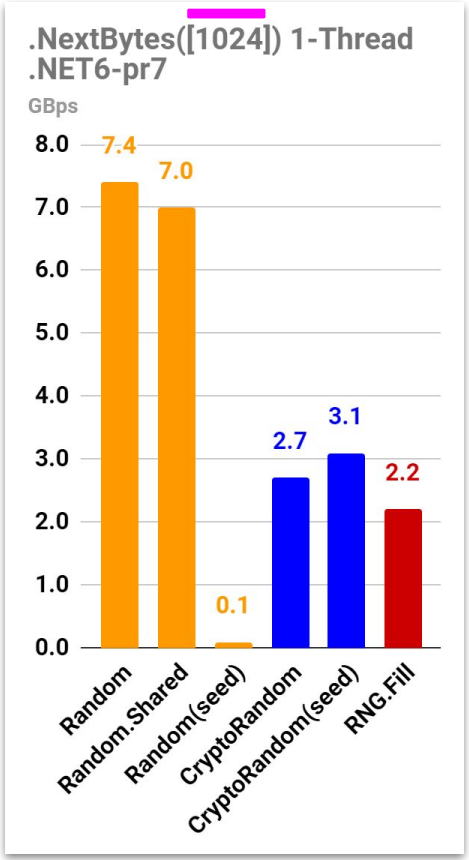
.NextBytes([1024]) 1-Thread
.NET6-pr7
GBps
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
7.4
7.0
0.1
2.7
3.1
2.2
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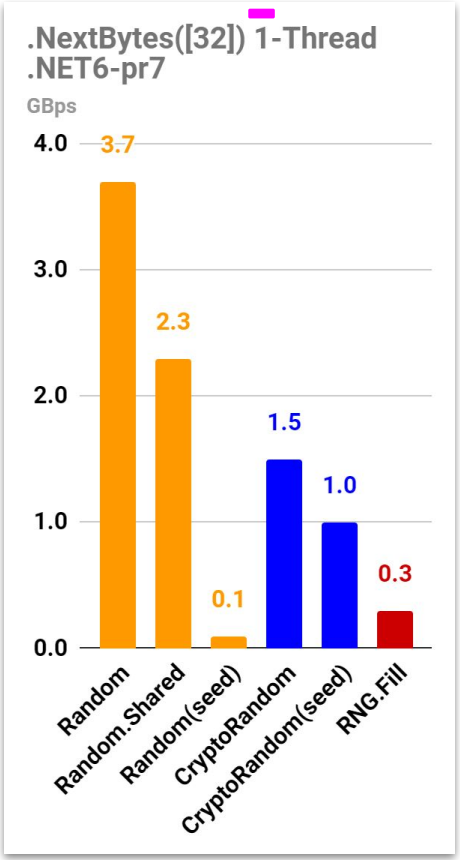
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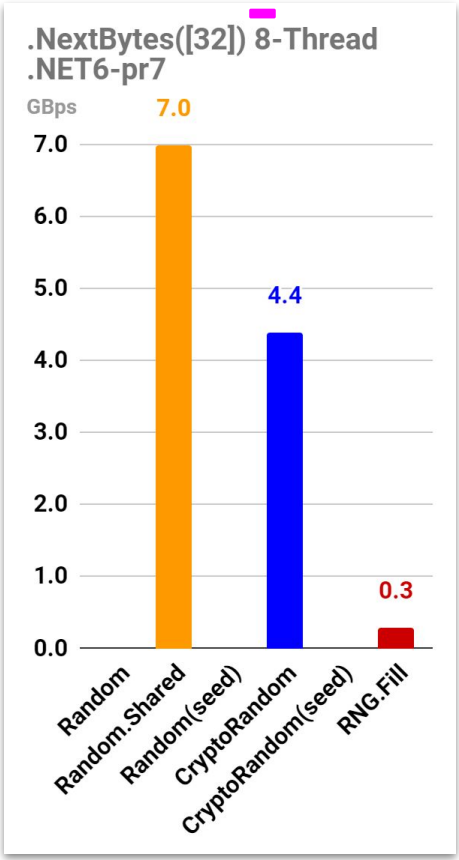
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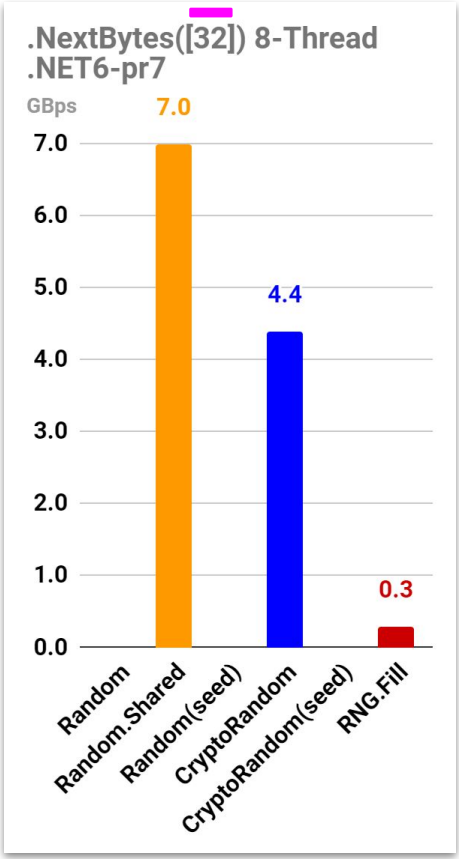
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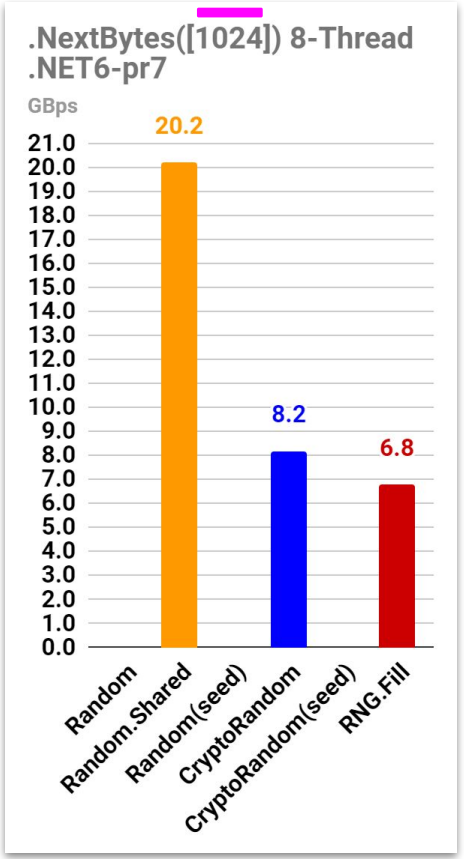
.NextBytes([1024]) 8-Thread
.NET6-pr7
GBps
20.2
8.2
6.8
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
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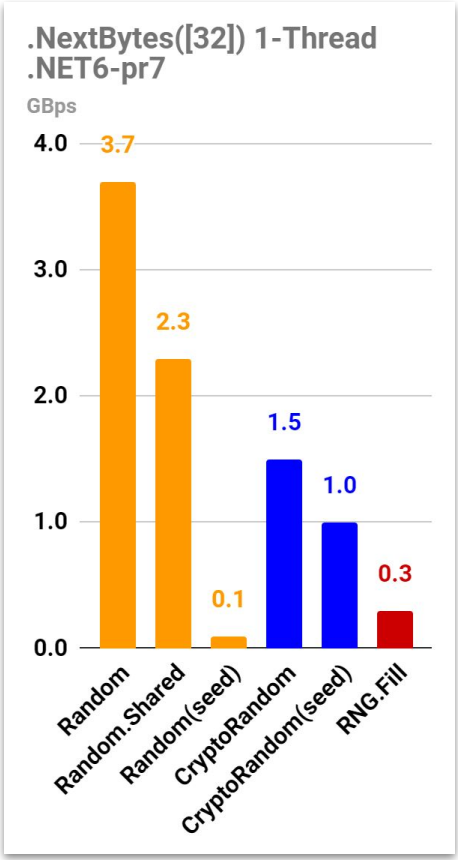

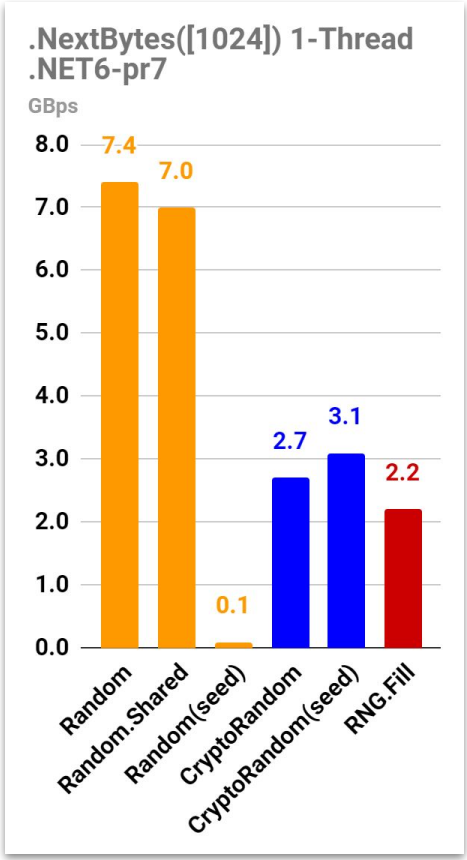

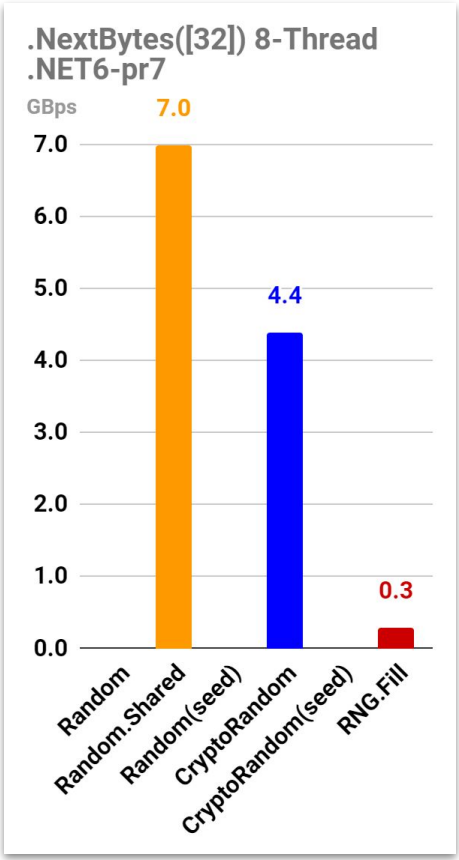

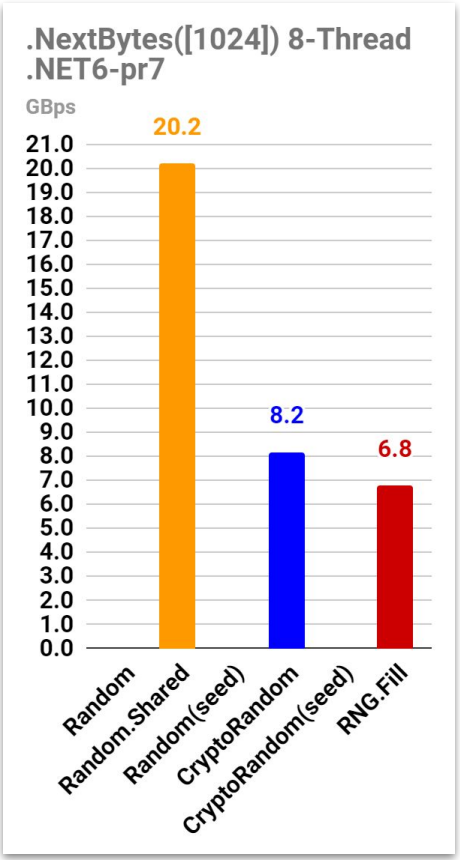

- Old Random (.NET <=5): ~0.1 GBps (1 thread, old laptop)
- New Random (.NET 6): ~7 GBps (1 thread, old laptop)
- CryptoRandom: ~3 GBps (1 thread, old laptop)

Call throughput of.Next() / .GetInt32()

Multi-threaded call-frequency perf:

- .Next() for Random API, and
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Old Random needs a Lock (.NET<=5).

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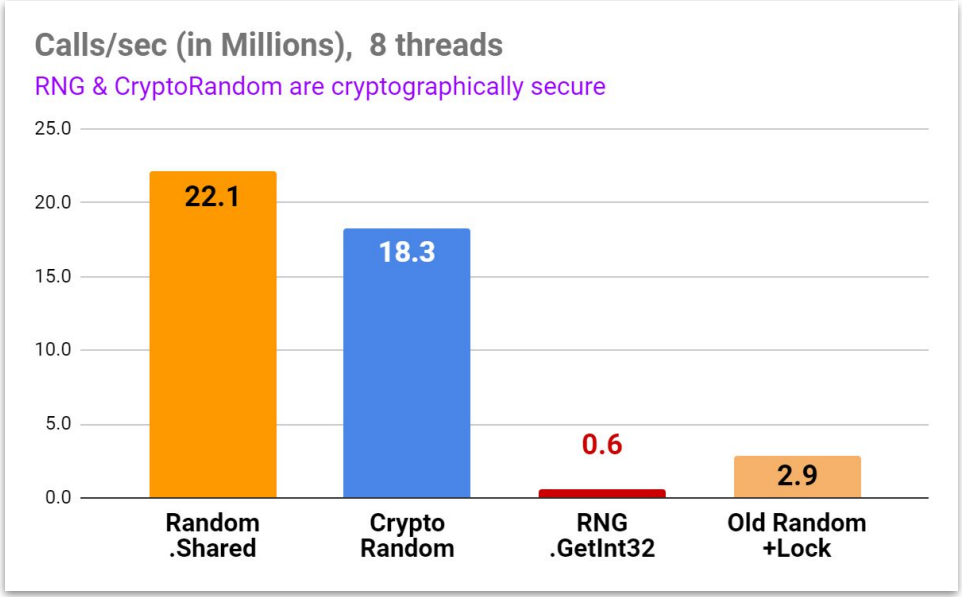

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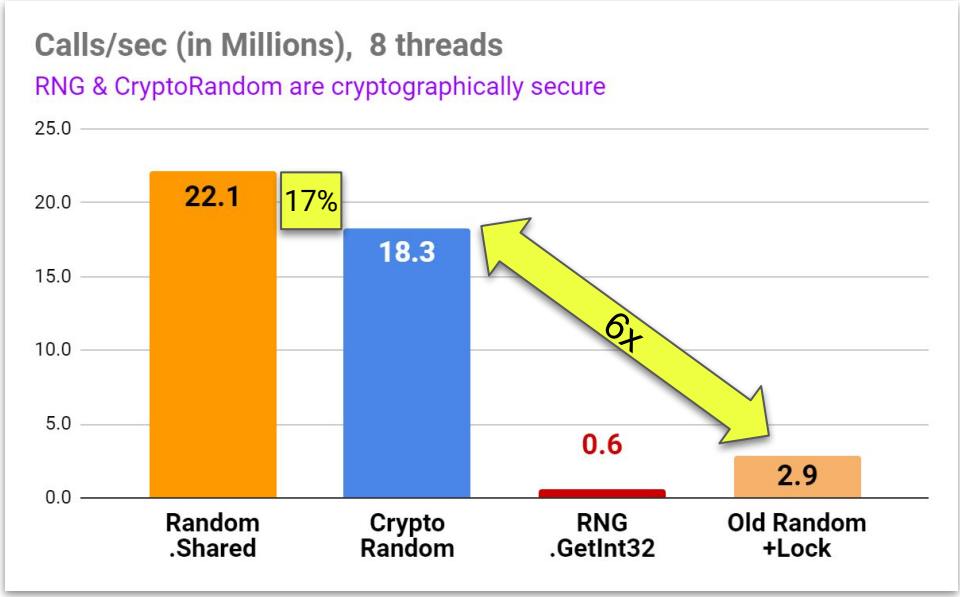
Is CryptoRandom fast enough? Yes.



new .NET 6 Random & CryptoRandom

- .NET 6 `Random()`/`xoshiro256**` predictable linear pseudo-random generator:
  - Very fast (`xkcd` random is even faster 😊)
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  - Fast enough for 99% of uses
  - Consider as your **new default** randomness provider

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- **CryptoRandom** is a fast, safe, secure drop-in for `Random`

Links

- Xoshiro generator family – David Blackman and Sebastiano Vigna
  - https://prng.di.unimi.it/
  - https://vigna.di.unimi.it/ftp/papers/ScrambledLinear.pdf
- Exploring Xoshiro Zeroland – Melissa O'Neill
  - https://www.pcg-random.org/posts/xoshiro-repeat-flaws.html
- .NET 6 implementation of Xoshiro
  - https://github.com/dotnet/runtime/blob/main/src/libraries/System.Private.CoreLib/src/System/Random.Xoshiro256StarStarImpl.cs
- DEF CON 29 – Dan Petro – You're doing IoT RNG
  - https://www.youtube.com/watch?v=Zuqw0-jZh9Y

Thank you!

Questions?

sdrapkin@sdprime.com

github.com/sdrapkin

Appendix

Other .NET 6 changes related to randomness

```
var r1 = RandomNumberGenerator.Create();
var r2 = RandomNumberGenerator.Create();
object.ReferenceEquals(r1, r2) ?
```

`False` in .NET <=5

- new RNG implementation object is created on every call

`True` in .NET 6

- RandomNumberGenerator.Create() returns a singleton object
- `Dispose()` is a no-op (calls GC.SuppressFinalize(this))

Other .NET 6 changes related to randomness

- `Guid.NewGuid()` is now guaranteed to contain 122 cryptographically strong random bits, on all .NET platforms (PR 42770)

- FastGuid .NET library (Nuget: “FastGuid”)
  - creates 128-bit strongly-random Guids
  - 10x faster on Windows vs `Guid.NewGuid()`
  - 30x faster on non-Windows vs `Guid.NewGuid()`
  - Scales per-core (ex. 4-core Linux → ~80x faster)

```
[Host] : .NET 6.0.0 (6.0.21.48005), X64 RyuJIT
|           Method |       Mean |    Error |   StdDev | Ratio |
|----------------- |-----------:|---------:|---------:|------:|
| FastGuid_NewGuid |   102.9 ns |  0.97 ns |  0.81 ns |  1.00 |
|     Guid_NewGuid | 1,101.9 ns | 21.76 ns | 30.50 ns | 10.67 |
```