A 20-20 View of Ada
An Evolutionary Perspective

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Ada-Europe 2019
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borrowed heavily from ...

AdaCore
TECH DAYS

Ada 2020 Update

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November 15, 2017
Ada83 to Ada2012—Lessons Learned Over 30 Years of Language Design

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October 2014
Safe Parallel Language Extensions for Ada 202X

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June 2014
Ada 2020 High-Level Story

- Make Ada a great language for parallel programming
- Other enhancements that build on Ada’s existing strengths:
  - Safety and Security
  - Contract-Based Programming
  - Expressivity (particularly when it furthers the previous goals)
Adding Support for Parallel Programming

Concurrent programming

- Multiple computations
- One or more workers
- Often need to synchronize between computations

Parallel programming

- One (or more) large computation(s)
- Many workers
- Synchronization typically only for work split/join
Adding Support for Parallel Programming

Concurrent programming

- Ada has great building blocks for concurrent programming
- Tasks, rendezvous, protected objects

Parallel programming

- Nothing currently built-in
- Although concurrent building blocks can be used, they’re very heavyweight
Ada 2020 Parallel Programming Goals

- Make it easy and safe to write parallel algorithms
- Hide the housekeeping of dispatch/scheduling/data collection
- Allow the compiler to choose among heterogeneous processors
  - $N$ threads/processors, GPU, coprocessors, etc..
- Have the compiler detect and disallow data races
A reminder why this is important...
The 2005 Right Turn in Single-Processor Performance (14 years ago)

Figure 2. Historical growth in single-processor performance and a forecast of processor performance to 2020, based on the ITRS roadmap. A dashed line represents expectations if single-processor performance had continued its historical trend.

Parallel Loops (2017)

```
parallel for I in 1 .. 1_000 loop
    A(I) := B(I) + C(I);
end loop;

parallel for Elem of Arr loop
    Elem := Elem * 2;
end loop;
```
Parallel Loops (202X)

```plaintext
parallel (2*Num_CPUs) -- Specify max level of parallelism
for I in 1 .. 1_000 loop
    A(I) := B(I) + C(I);
end loop;

parallel (Ck in Partial_Sum’Range) -- A named chunk index
for Elem of Arr loop
    Elem := Elem * 2;
    Partial_Sum(Ck) := @ + Elem ** 2; -- Manual reduction
end loop;
Sum := Partial_Sum’Reduce(“+”, 0.0); -- Final reduction
```
Parallel Block (2014)

```
parallel
  sequence_of_statements
{and
  sequence_of_statements}
end parallel;
```

*From “Gang of 4” HILT 2014 paper:*
Each alternative is an (explicitly specified) “parallelism opportunity” (POp) where the compiler may create a *tasklet*, which can be executed by an *execution server* while still running under the context of the enclosing *task* (same task ‘Identity, attributes, etc.). Compiler will complain if any data races or blocking are possible (using Global and Potentially_Blocking aspect information).*
Parallel Block (202X)

```
parallel do
    handled_sequence_of_statements
{and
    handled_sequence_of_statements}
end do;
```

*From Ada 202x draft manual:*
Each handled_sequence_of_statements represents a separate logical thread of control that proceeds independently and concurrently. The parallel_block_statement is complete once every one of the handled_sequence_of_statements has completed, either by reaching the end of its execution, or due to a transfer of control out of the construct by one of the handled_sequence_of_statements (see 5.1).

- **Parallel block is important for divide-and-conquer algorithms**
  - such as sorting and searching
  - equivalent to parallel loop around a “case” statement
-- A reduction expression to calculate the sum of elements of an array
Result : Integer := (for Element of Arr => <0> + Element)

-- A reduction expression to create an unbounded string
-- containing the alphabet
Alphabet : Unbounded_String := (for Letter in 'A' .. 'Z' => <Null_Unbounded_String> & Letter)

-- A reduction expression to determine how many
-- people in a database are 30-something
ThirtySomethings : constant Natural := (for P of Personnel => <0> + (if Age(P) > 30 then 1 else 0)));
Map/Reduce Iterators (202X)

-- A reduction expression to calculate the sum of elements of an array
Result : Integer := [for Element of Arr => Element]’Reduce(“+”, 0);

-- A reduction expression to create an unbounded string
-- containing the alphabet
Alphabet : Unbounded_String
  := [for Letter in 'A' .. 'Z' => Letter]’Reduce(“&”, Null_Unbounded_String, “&”);

-- A reduction expression to determine how many
-- people in a database are 30-something
ThirtySomethings : constant Natural
  := [for P of Personnel => (if Age(P) > 30 then 1 else 0)]’Reduce(“+”, 0);
Global contracts from SPARK (2017) used for data race detection

Global => **in out all** -- default for non-pure pkgs
Global => **null** -- default for pure packages

-- Explicitly identified globals with modes
Global => (in P1.A, P2.B,
            in out P1.C,
            out P1.D, P2.E)

-- Pkg data, access collection, task/protected/atomic
Global => **in out** P3 -- pkg P3 data
Global => **in out** P1.Acc_Type -- acc type
Global => **in out synchronized** -- prot/atomic
Global contracts from SPARK (202X) used for data race detection

Global => **in out all**  -- default for non-pure pkgs
Global => **null**       -- default for pure packages

-- Explicitly identified globals with modes
Global => (**in** P1.A, P2.B,
           **in out** P1.C,
           **out** P1.D, P2.E)

-- Pkg data, access collection, task/protected/atomic
Global => **in out private of** P3  -- pkg P3 data
Global => **in out** P1.Acc_Type     -- acc type
Global => **synchronized in out all** -- prot/atomic
Nonblocking contract
used for deadlock detection

• Ada 202X Nonblocking aspect
  -- apply to one subprogram
  procedure Suspend_Until_True
    (S : in out Suspension_Object)
    with Nonblocking => False;

  -- apply to an entire package
  package Ada.Characters.Handling
    with Nonblocking => True is ...

• Similar to “queued” qualifier in ParaSail
Ada 202x Syntactic Building Blocks for Parallelism
Ada 202X Building Blocks -- Iterators

- **Programmers Prefer Iterators**
  - Looping semantics very visible -- no mystery
  - Ada 2012 iterators made containers significantly more useful
    - E.g. AdaCore tool written in 2013 makes heavy use of iterators

- **In Ada 202X, we build on iterators**
  - For array aggregates defined with “iterated component association”:
    - X : Int_Array := (for I in 1..N => I**2)
  - For aggregates defined by iterating over a container:
    - Y : Int_Array := (for E of C => E);
  - For “procedural iterators”:
    - Loop body becomes local anonymous procedure passed into existing iterator procedures:
      - such as Maps.Iterate and Environment_Variables.Iterate
  - For reduction expressions (see earlier examples)
Ada 202X Building Blocks -- Filters

• **Iterators sometimes generate too many values**
  ○ Use filter to reduce to values of interest
  ○ *for* iterator *when* condition ...

• **Filters can be used in various kinds of iterators:**
  ○ For aggregates defined by iterating over a container:
    ■ Odds : Int_Array := (for E of C when E mod 2 = 1 => E);
  ○ For procedural iterators:
    ■ *for* (Name, Value) of Environment_Variables.Iterate
      *when* Name(Name’First) /= “_” *loop*
      Put_Line (Name & “ => “ & Value);
      *end loop*;
  ○ For reduction expressions:
    ■ *[for* P of Personnel *when* Age(P) > 30 => 1]*’Reduce(“+”, 0);
Ada 202X Building Blocks -- “parallel”

- Iterators can generate many values
  - Use “parallel” to spawn multiple logical threads of control
    - `parallel ...` -- uses default amount of “chunking”
    - `parallel (Num_Chunks) ...` -- specify a max number of chunks
    - `parallel (Chunk in 1..Num_Chunks) ...` -- specify a chunk parameter

- “parallel” can be used with various kinds of iterators:
  - For iterating over a large range:
    - `parallel (Chunk in 1 .. Num_Chunks)` -- named chunk parameter
    - `for I in Arr’Range loop`  
      - `...`  
        - `Partial_Sum(Chunk) := @ + Arr(I);` -- accumulator for each chunk
      - `end loop;`
    - `return Partial_Sum’Reduce(“+”, 0.0);` -- final reduction
  - For large reduction expressions over container iterator:
    - `[parallel for P of Personnel when Age(P) > 30 => 1]’Reduce(“+”, 0);`
    - User defined “split” iterators for containers -- like Java’s “spliterators”
  - Data race conflict checks provided at three levels -- All, Known, None
Ada 202x uses “building block” approach

- Enabled by orthogonality of syntax
- Eases use and readability relative to large library or multiple pragmas
- Portable concepts that can be mapped to diverse targets
- Compile-time conflict checking for safety
Relevance of OpenMP & friends

- **OpenMP 1.0**  -- 1997, OpenMP ARB
  - *Heavy weight threads, SPMD model*
- **CUDA**  -- 2007, NVIDIA
  - *NVIDIA GPUs, explicit separated “kernel” code*
- **OpenCL**  -- 2008, Apple, Khronos
  - *Most GPUs, explicit separated “kernel”s*
- **OpenMP 3.0**  -- 2008, OpenMP ARB
  - *Lighter weight “tasks” with work sharing*
- **OpenACC**  -- 2011, Cray, NVIDIA, PGI
  - *Many GPUs, no separate “kernel”*
  - *Extracts GPU “kernel” code from for-loop*
- **OpenMP 4.0**  -- 2013, OpenMP ARB
  - *Adds “target” devices, begins to subsume OpenACC*
- **OpenMP 5.0**  -- 2018, OpenMP ARB
  - *Largely subsumes OpenACC, and OpenCL to lesser extent*
OpenMP Evolution

- OpenMP originally designed in 1997
  - Initially supported only heavy-weight “threads”
    - mapped generally to “kernel” threads
    - analogous to Ada “tasks”
  - Thread ID used explicitly to compute what part of data to manipulate
    - SPMD -- “Single Program, Multiple Data” model
  - Programs had no visible structure that matched computation being performed
    - Pragmas used heavily to provide implicit structure
    - No data race checking provided

- OpenMP evolved over time; OpenMP 5.0 is recently released (Nov 2018)
  - Early features mostly supplanted by newer notions based on lighter-weight “tasks” and work sharing.
  - Supports parallel loops of a specific structure (pragma + pattern)
  - Supports parallel blocks using an explicit “task” pragma
  - Incorporated OpenACC-like support for “targets” such as GPUs
  - Preferred over OpenCL or CUDA because can debug parallel algorithm on host before inserting “target” directives
  - Still no data race checking in most implementations
    - Explicit dependence annotations could eventually enable more checking
Mapping Ada 202X to OpenMP & friends

- **For Ada 202X mapping, we will generally use newer OpenMP features**
  - Rely on Ada 202x language syntax for high-level parallel algorithm structure
    - including correctness and highest level tuning (e.g. chunking)
  - Rely on pragmas, aspects, and/or library calls for target-specific tuning:
    - Controlling total number of heavy-weight threads
    - Data flushing and caching
    - Mapping to target devices

- **Examples of specific mappings:**
  - **Parallel region establishes initial number of (heavyweight) threads**
    - Generally will create one region per Ada program
    - Want to minimize creating and releasing multiple heavyweight threads
  - **For parallel block, tasks are generated**
    - a “single” construct followed by two or more “task” pragmas (or API calls)
    - awaited at a “taskwait”
  - **For parallel loop:**
    - “parallel for” or “taskloop” pragma/API used for loops that match for-loop “pattern” supported by OpenMP
    - tasks spawned explicitly to handle other Ada 202X parallel loops, such as those for parallel container iterators, with explicit “taskwait”
Reprise:
Ada 2020 Parallel Programming Goals

- Make it easy and safe to write parallel algorithms
- Hide the housekeeping of dispatch/scheduling/data collection
- Allow the compiler to choose among heterogeneous processors
  - N threads/processors, GPU, coprocessors, etc..
- Have the compiler detect and disallow data races
Ada 2020 Expressivity Features

- Allow user to express their intent with less boilerplate
- More declarative fashion of doing things:
  - Usable in contracts
  - Smaller bug surface
Ada 2020 Expressivity Features (2017)

- **Delta aggregate notation**: Update only part of a data structure

```ada
Tax_Day : Date := (Today with delta Day => 15, Month => April);
```

- **Array aggregates defined by an Iterator**

```ada
Squares : array (Positive range <>) of Integer := (for I in 1 .. 256 => I ** 2);
```

- **Aggregates for containers** *(can be combined with previous features)*

```ada
package Maps is new Ada.Containers.Hashed_Maps (Integer, String, ..);

M : Maps.Map := (1 => "Hello", 2 => "World");
```
Ada 2020 Expressivity Features (202X)

-Delta aggregate notation: Update only part of a data structure

```
Tax_Day : Date := (Today with delta Day => 15, Month => April);
```

-Array aggregates defined by an Iterator

```
Squares : array (Positive range <>) of Integer := (for I in 1 .. 256 => I ** 2);
```

-Aggregates for containers (can be combined with previous features)

```
package Maps is new Ada.Containers.Hashed_Maps (Integer, String, ...);
package String_Sets is new Ada.Containers.Hashed_Sets (String, ...);

M : Maps.Map := [1 => "Hello", 2 => "World"];  
S : String_Sets.Set := [];  -- Empty set
begin
  S := ["Hello"];  -- Singleton set
```

-Declare expressions

```
with Post => (declare M renames Integer’Max(X, Y); begin F’Result = 2*M / (M-1))
```
Other Ada 202X Significant Changes

- Pre and Post for access-to-subprogram types and for generic formals
- Default_Initial.Condition to specify state after default initialization of a private type
- Pre, Post, Nonblocking, Global used to specify container packages
- Stable view for containers to support more efficient iteration
- Static expression functions
- The Image attribute for nonscalar types (arrays, records, etc.)
- User-specifiable attribute Put_Image provides user-defined Image
- User-defined Integer_Literal, Real_Literal, and String_Literal aspects.
- Arbitrary-precision integer and real arithmetic
- The Jorvik profile for lower criticality hard-real time systems
Ada 202X
Prototyping and Evaluation
(cf. Ada 80 Test & Eval)

Example Issues:
- CPU vs. GPU vs. OpenMP focus
- Race Condition and Deadlock Checking
- Syntax vs. Pragmas vs. Library
- Overall Ease of Understanding
- Getting the Details Right
Ada 202X Feedback Time!

● Importance of supporting lightweight parallelism in Ada 202X
  ○ 1 = Not important, 5 = Very important

● Which is likely more important for Ada 202X users:
  ○ multicore CPUs
  ○ GPUs
  ○ no difference

● Importance of Race Condition and Deadlock Checking
  ○ 1 = Not important, 5 = Very important

● Favored approach to lightweight parallelism for Ada 202X
  ○ Syntax
  ○ Pragmas
  ○ Library
Ada 202X Feedback Time!

- Array aggregates defined by an Iterator

Squares : array (Positive range <> ) of Integer := (for I in 1 .. 256 => I ** 2);

- Aggregates for containers (can be combined with previous features)

package Maps is new Ada.Containers.Hashed_Maps (Integer, String, ...);
package String_Sets is new Ada.Containers.Hashed_Sets (String, ...);

M : Maps.Map := [1 => "Hello", 2 => "World"];  
S : String_Sets.Set := []; -- Empty set
begin
  S := ["Hello"]; -- Singleton set

1. Use [...] for container aggregates only
2. Use [...] for container aggregates, and allow for array aggregates
3. Use [...] for container aggregates, and allow for any aggregate
4. Don‘t use [...] for container aggregates
   a. empty and singletons should use some other special syntax
Whither Ada 2099?
Ada 83

• Rock Solid Abstraction Capability
  • Packages and Private Types
  • Very Strongly Distinguished Numeric Types

• Completely Static Language
  • No Type Extension
  • No Procedure Parameters
  • No Runtime Polymorphism
  • Case Statements Rule the World
Ada 95

- A Radical New Style – Very Dynamic
  - Case Statements Considered Harmful
  - Inheritance and Polymorphism are the new Style
- But Ada 95 was a bit spikey
- Some features not fully integrated
  - OO and Tasking don’t play together well
  - Generics and OO are awkward partners
- No notion of Abstract Interfaces
- Relatively Low-Level Standard Libraries
Ada 2005

- Integrated OO and Tasking – Far out
- Rounded off the spikey corners of Ada 95
- Created a Library of Containers
  - Lists, Vectors, Sets, Maps
  - Encapsulate the Complexity
  - Raise the Level of Abstraction
  - But Containers Are A Bit of a Pain to Use
- But not very exciting, no new killer apps
- Still Haven’t Addressed Awkward Generic/OO Partnership
  - Each generic instance represents a completely separate type hierarchy
Ada 2012

- Don’t mess with Ada 2012
- Enforces Contract-Based Programming
- Gives Programmers More Power
  - Conditional Expressions
  - Quantified Expressions
  - High-Level Container Iterators
- But Elegant High-Level Features Depend on Ever-Expanding Complexity Below
  - Dynamic object lifetime checks
  - Tampering Checks
  - Storage Subpools
  - Aliased Parameters
- Generics Remain Too Heavyweight
  - And not smoothly integrated into type hierarchy
Ada 202x -- Ada 2099  A New Start?

- Multicore revolution is a chance to rethink some basic assumptions
- Safety Through Simplification a la SPARK
  - Alias-free Pointers
  - Declared Side-Effects
  - Absence of Runtime Exceptions (AoRTE)
  - Generics and OO Integrated Smoothly
  - Syntactic Sugar Provides Uniform High-Level Abstractions
- Lightweight Safe Parallelism for all Iterators
- Still Looks and Feels Familiar while Reducing Complexity and Gaining Safety
Beam me up!