VECTORIZATION CASE STUDY

INTEL® ADVISOR – VECTORIZATION ADVISOR

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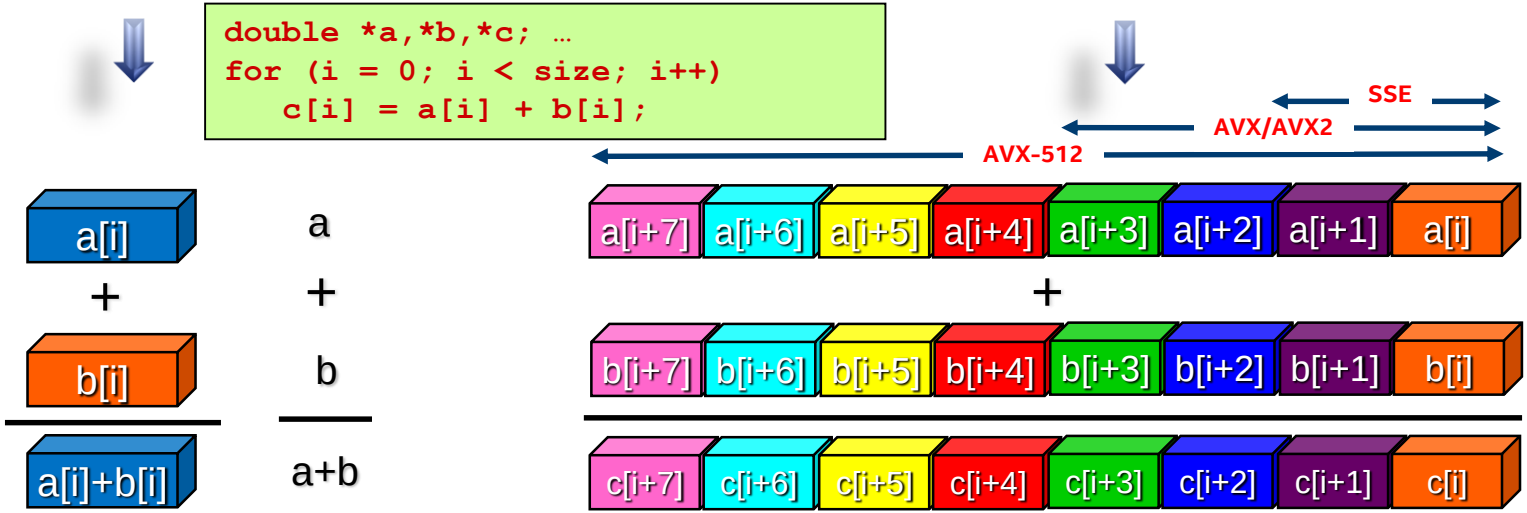
Special thanks to Alex Shinsel (Consulting Engineer, Intel)

SIMD => **S**ingle **I**nstruction **M**ultiple **D**ata

VLP / Vectorization

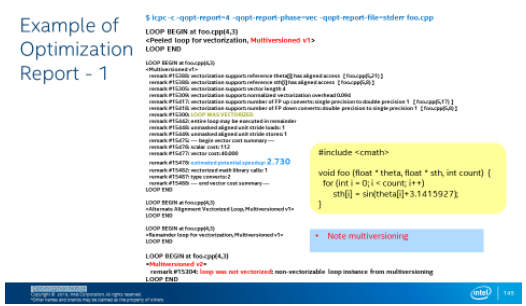
- **Scalar**
  - one instruction produces one result
- **SIMD processing**
  - one instruction can produce multiple results (SIMD)
  - e.g. vadd**p**d / vadd**p**s (p => packed)

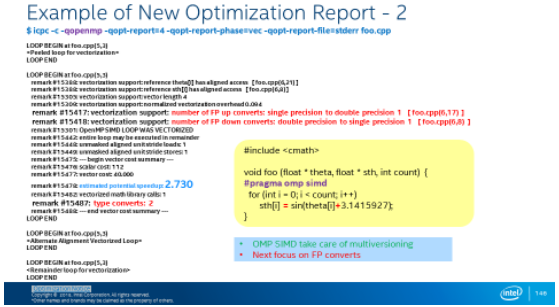


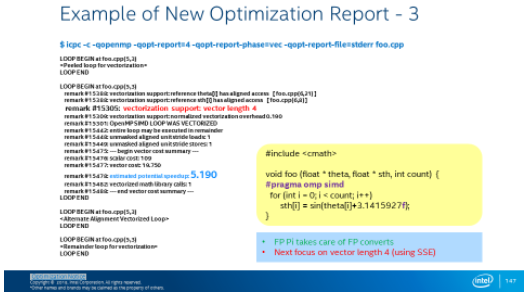
Outline from Previous Lectures on Vectorization

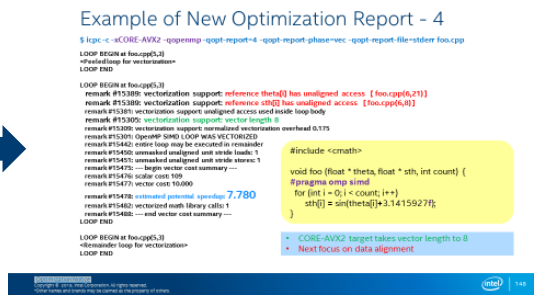
- What is vectorization and why is it important
- The different ways we can vectorize our code
- The two main challenges in vectorization
  - Determining that vectorization is legal (the results will be the same)
    - Dependence analysis
    - Obstacles to vectorization and how to deal with them
  - Optimizing performance
    - Memory issues (alignment, layout)
    - Telling the compiler what you know (about your code & about your platform)
- Using compiler intrinsics
- Using OpenMP* simd pragmas
- A case study

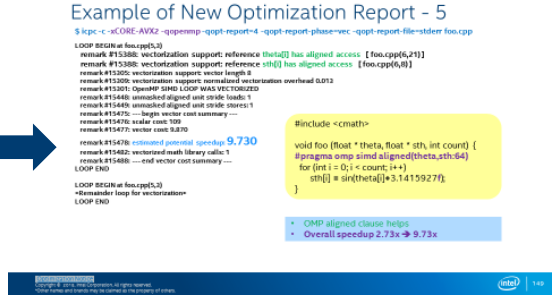
In previous lectures on vectorization:











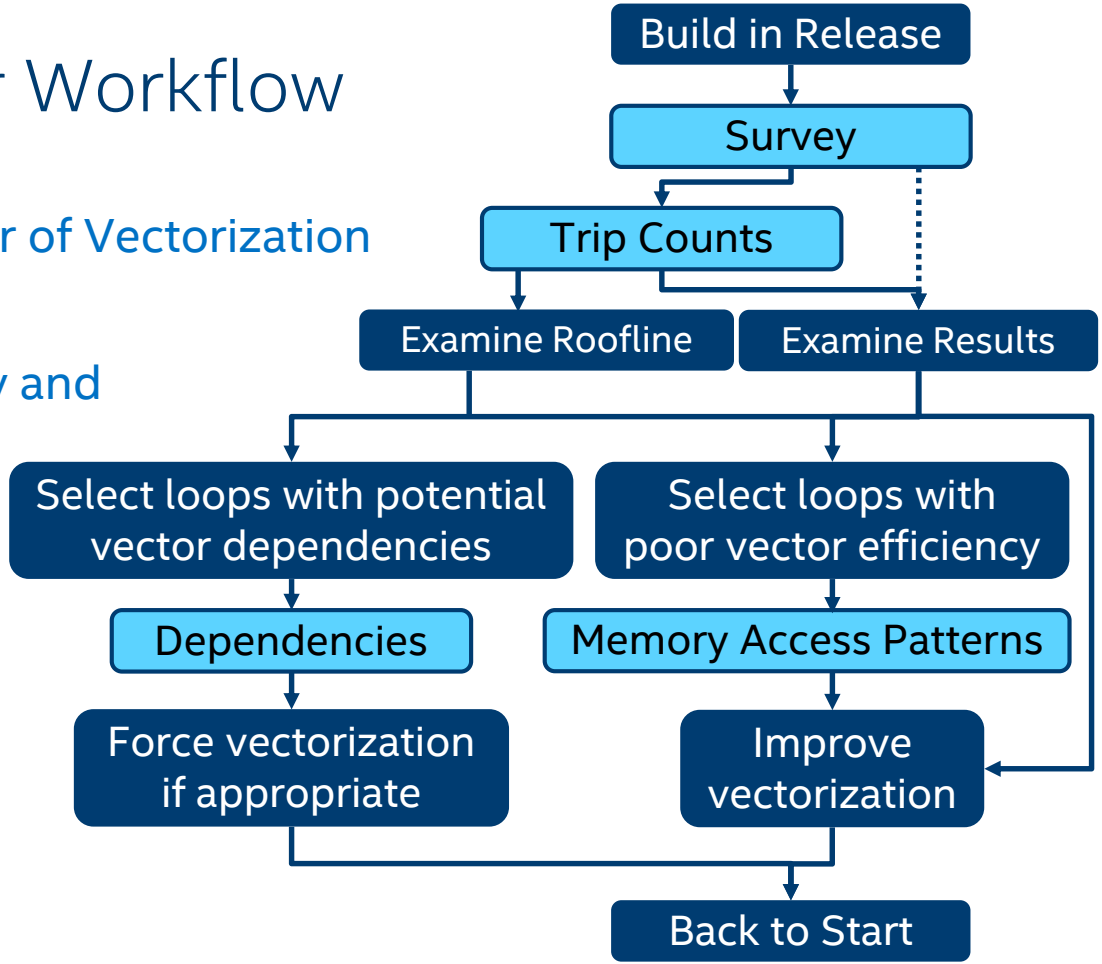
USING INTEL® ADVISOR TO ASSIST WITH VECTORIZATION

Based on a presentation by Alex Shinsel

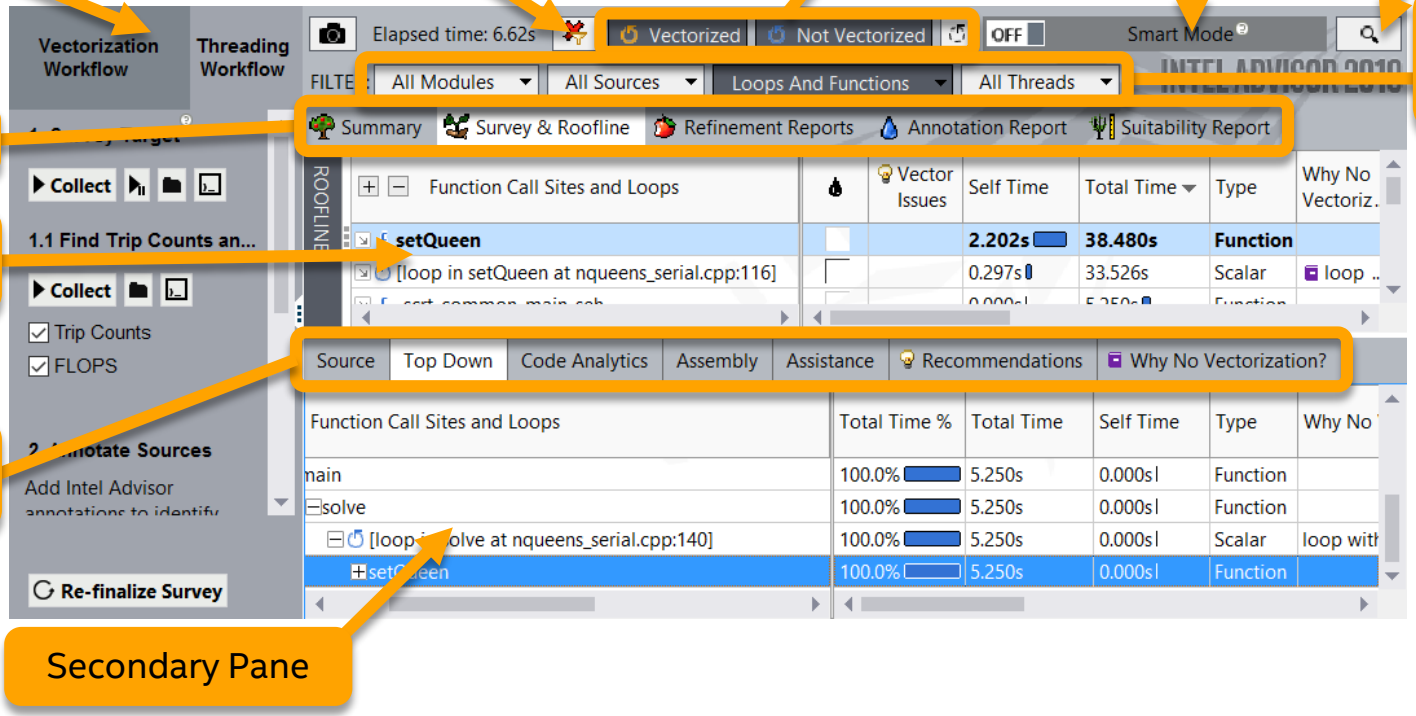

Vectorization Workflow
Threading Workflow
OFF
Batch mode
Run Roofline
Collect
1. Survey Target
Collect
1.1 Find Trip Counts and FL...
Collect
Trip Counts
FLOPS
Mark Loops for Deeper Anal...
Select loops in the Survey Report for Dependencies and/or Memory Access Patterns analysis.
-- There are no marked loops --
2.1 Check Dependencies
Collect
-- Nothing to analyze --
2.2 Check Memory Access P...
Collect
Re-finalize Survey
VECTORIZATION ADVISOR & ROOFLINE

Vectorization Advisor Workflow

- **Survey** is the bread and butter of Vectorization Advisor! All else builds on it!
- **Trip Counts** adds onto Survey and enables the **Roofline.**
- **Dependencies** determines whether it's safe to force a scalar loop to vectorize.
- **Memory Access Patterns** diagnoses vectorization inefficiency caused by poor memory striding.



What Am I Looking At?



Survey
Vectorization Advisor

Tip:

For vectorization, you generally only care about loops. Set the type dropdown to “Loops”.

Efficiency is important!

$$\text{Efficiency} = 100\% \frac{\text{Speedup}}{\text{Vec. Length}}$$

The black arrow is 1x. Gray means you got less than that. Gold means you got more. You want to get this value as high as possible!

Function/Loop Icons

- Scalar Function
- Vector Function
- Scalar Loop
- Vector Loop

Vectorizing a loop is usually best done on innermost loops. Since it effectively divides duration by vector length, you want to target loops with high self time.

Function Call Sites and Loops	Vector Issues	Self Time	Total Time	Type	Why No Vectorization?	Vectorized Loops			
						Vect...	Efficiency	Gain...	VL
[loop in main at example.cpp:38]	1 Assumed depend...	0.391s	0.391s	Scalar	vector depen...				
[loop in main at example.cpp:64]	1 Possible inefficien...	0.297s	0.297s	Vector...		AVX2	2%	0.37x	16
[loop in main at example.cpp:51]	1 Possible inefficien...	0.094s	0.094s	Vector...	1 vectorizatio..	AVX2	8%	1.23x	16
[loop in main at example.cpp:26]		0.030s	0.030s	Vector...		AVX2	100%	7.98x	8
[loop in main at example.cpp:14]	3 Assumed depend...	0.000s	0.000s	Scalar	vector depen...				
[loop in main at example.cpp:23]		0.000s	0.030s	Scalar	inner lo...w...				

Expand a vectorized loop to see it split into body, peel, and remainder (if applicable).

Advisor *advises* you on potential vector issues. This is often your cue to run MAP or Dependencies. Click the icon to see an explanation in the bottom pane.

The Intel Compiler embeds extra information that Advisor can report in addition to its sampled data, such as why loops failed to vectorize.

Let’s look at an example…

Trip Counts

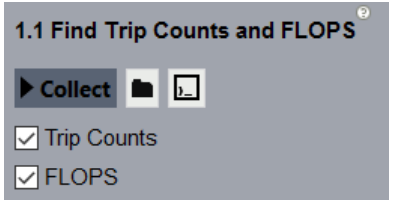
- Trip Counts extends the Survey results. It must be run separately because it has higher overhead that would interfere with timing measurements.
- Vectorization is most effective on inner loops with high iteration counts.
  - It may be beneficial to swap small inner loops and larger outer loops.
  - For maximum performance, iteration counts that are a multiple of the vector length are ideal.
- Trip Counts is useful in diagnosing data alignment and padding problems in loops that traverse multidimensional arrays.
  - In such cases, the trip counts on peel and remainder loops may change as rows/columns push each other out of alignment.

Function Call Sites and Loops	Type	Trip Counts					
		Average	Min	Max	Call Count	Iteratio...	Loop I...
[loop in main at dat...	Vectorized (Body; ...	4374; 5; 4	4374; 1; 1	4375; 7; 7	400000; 34...	< 0.001s	
[loop in main at ...	Vectorized (Body)	4374	4374	4375	400000	< 0.001s	< 0.001s
[loop in main at ...	Remainder	5	1	7	348000	< 0.001s	< 0.001s
[loop in main at ...	Peeled	4	1	7	352000	< 0.001s	< 0.001s

… and FLOPS

Part of the Trip Counts Collection

- Trip Counts and FLOPS are the same collection type, but can be toggled independently using the checkboxes in the workflow or command line flags.
- FLOPS collects information about Floating Point Operations, or FLOPs. This is used with Survey data to calculate **FLOPS, Floating Point Operations Per Second.**
- It also collects some memory data, so it can calculate Arithmetic Intensity.
- **Arithmetic Intensity** is a measurement of **FLOPs/Byte accessed**. This is a trait of the algorithm of a function/loop itself.



FLOPS

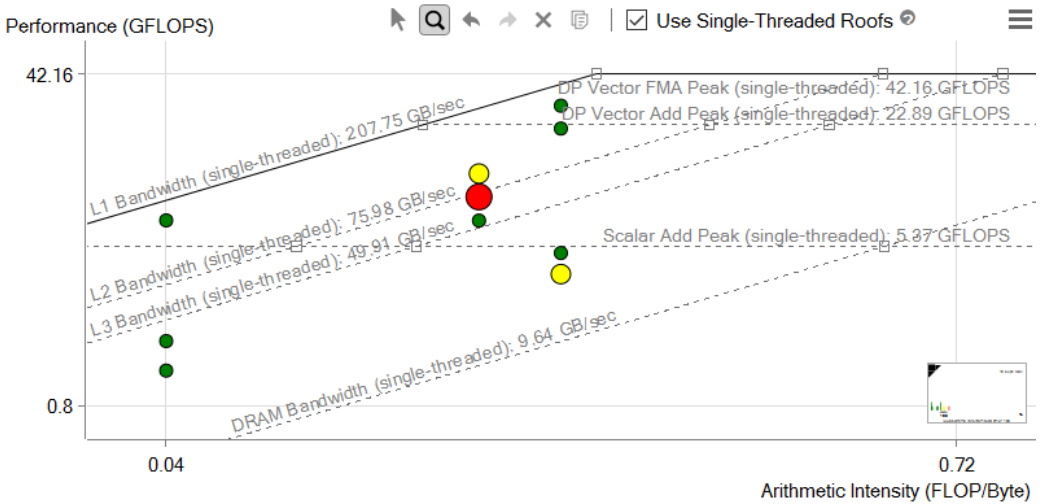
GFLOPS	AI	GFLOP	Memory, GB	Elapsed Time	Total El…
3.917	0.179	53.120	296.831	13.562s	13.562s
1.756	0.045	13.280	296.831	7.563s	7.563s
7.249	0.134	53.120	395.775	7.328s	7.328s
19.999	0.179	53.120	296.831	2.656s	2.656s
7.264	0.045	13.280	296.831	1.828s	1.828s

Let’s look at our example again…

What is a Roofline Chart?

A Roofline Chart plots application performance against hardware limitations.

- Where are the bottlenecks?
- How much performance is being left on the table?
- Which bottlenecks can be addressed, and which *should* be addressed?
- What's the most likely cause?
- What are the next steps?



Roofline first proposed by University of California at Berkeley:
Roofline: An Insightful Visual Performance Model for Multicore Architectures, 2009
Cache-aware variant proposed by University of Lisbon:
Cache-Aware Roofline Model: Upgrading the Loft, 2013

Roofline Metrics

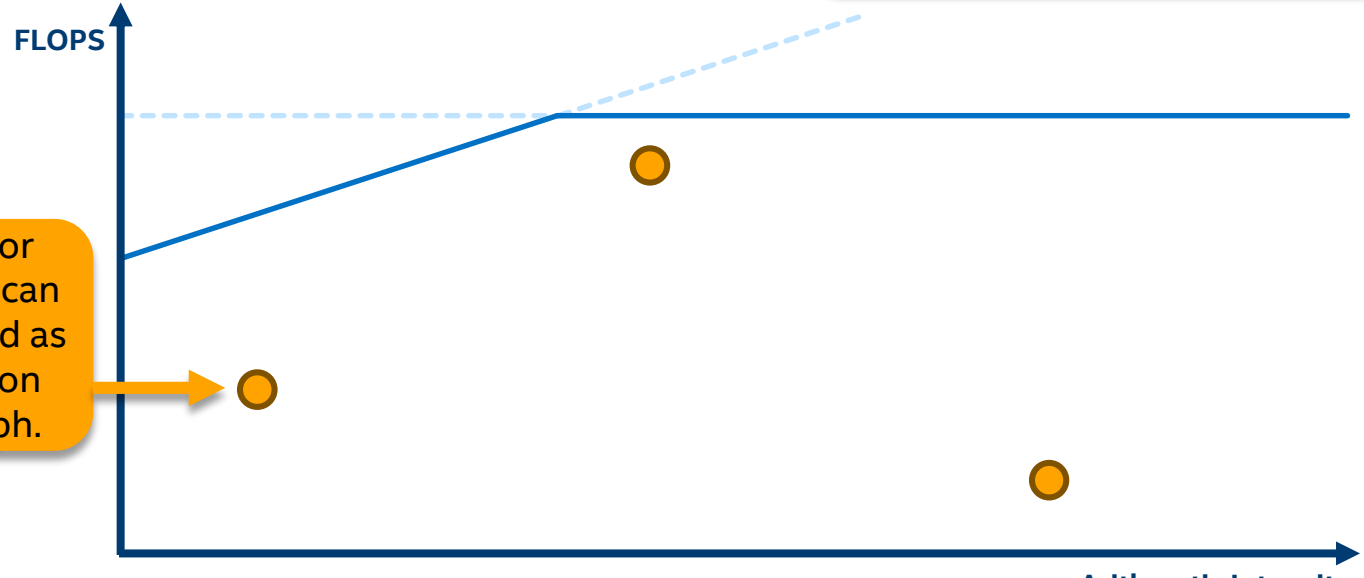
Roofline is based on Arithmetic Intensity (AI) and FLOPS.

- **Arithmetic Intensity**: FLOP / Byte Accessed
  - This is a characteristic of your algorithm

- **FLOPS**: **Fl**oating-Point **Op**erations / **S**econd
  - Is a measure of an implementation (it achieves a certain FLOPS)
  - ***And*** there is a maximum that a platform can provide

Plotting a Roofline Chart

The maximum FLOPS as a product of ops/byte (AI) and maximum bytes supplied per second is a diagonal line.



A loop or function can be plotted as a point on the graph.

The CPU's maximum FLOPS can be plotted as a horizontal line.

A Roofline Chart uses AI as its X axis and FLOPS as its Y axis.

Classic vs. Cache-Aware Roofline

Intel® Advisor uses the Cache-Aware Roofline model, which has a different definition of Arithmetic Intensity than the original ("Classic") model.

Classical Roofline

- Traffic measured from one level of memory (usually DRAM)
- AI may change with data set size
- AI changes as a result of memory optimizations

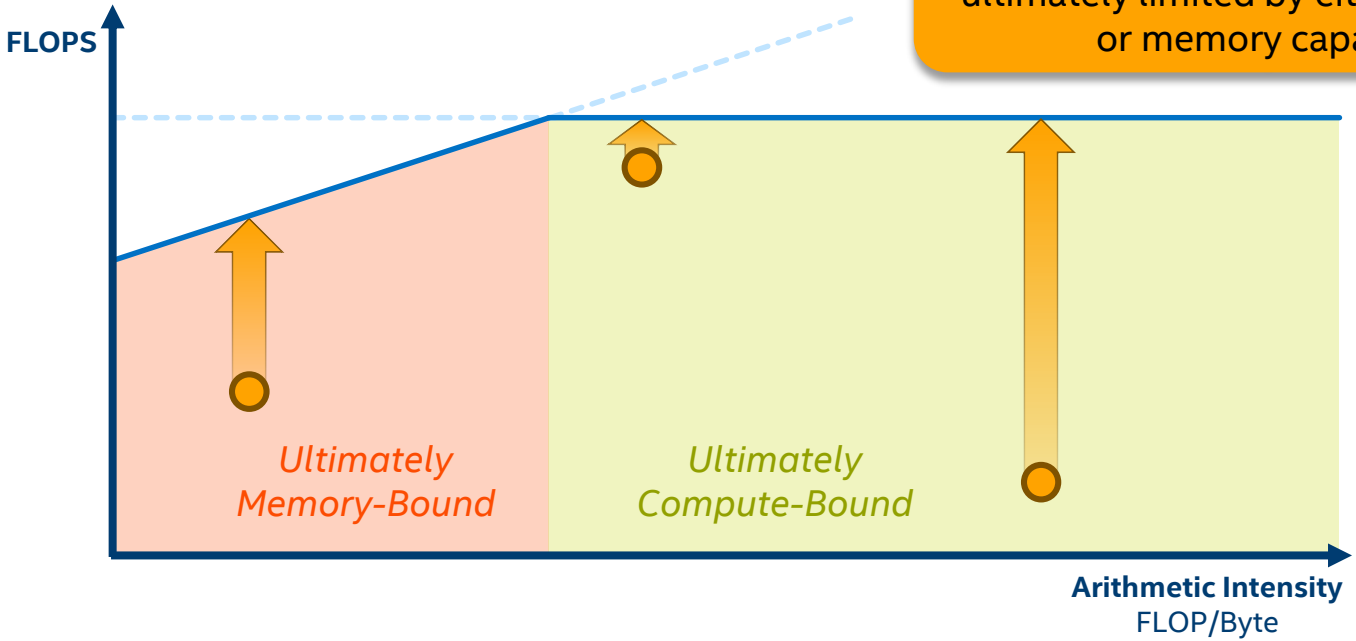
Cache-Aware Roofline

- Traffic measured from all levels of memory
- AI is tied to the algorithm and will not change with data set size
- Optimization does not change AI*, only the performance

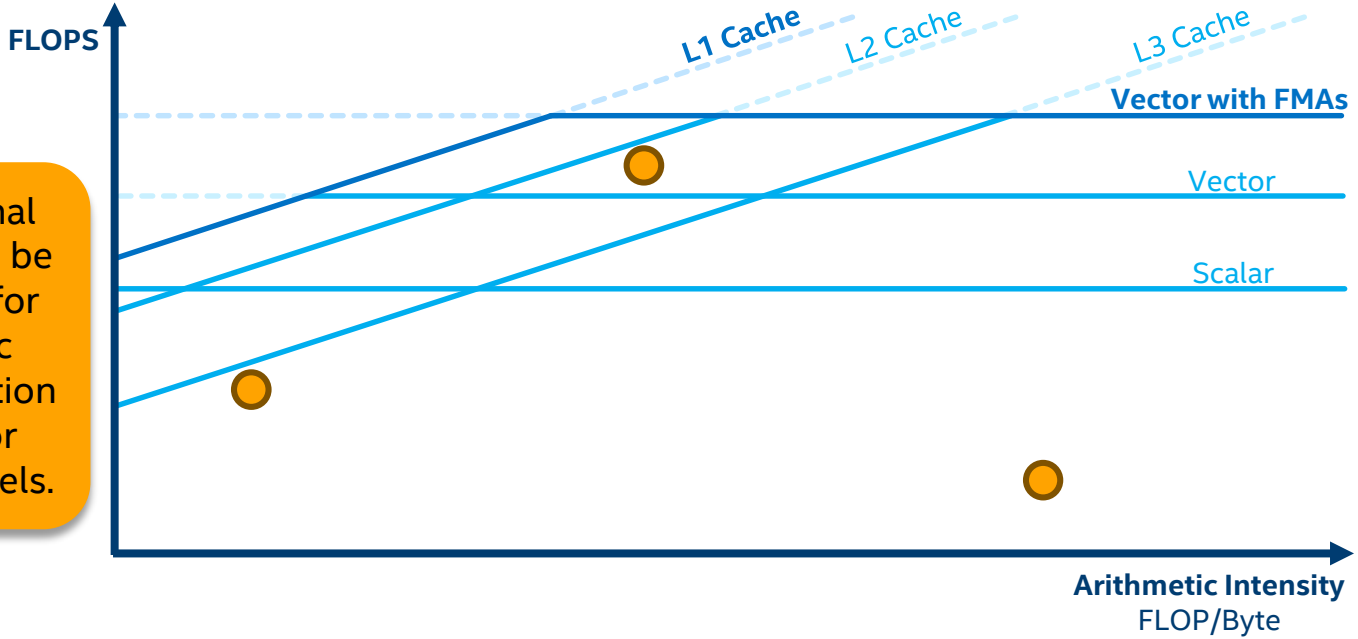
**Compiler optimizations may modify the algorithm, which may change the AI.*

Ultimate Performance Limits

Performance cannot exceed the machine's capabilities, so each loop is ultimately limited by either compute or memory capacity.



Sub-Roofs and Current Limits

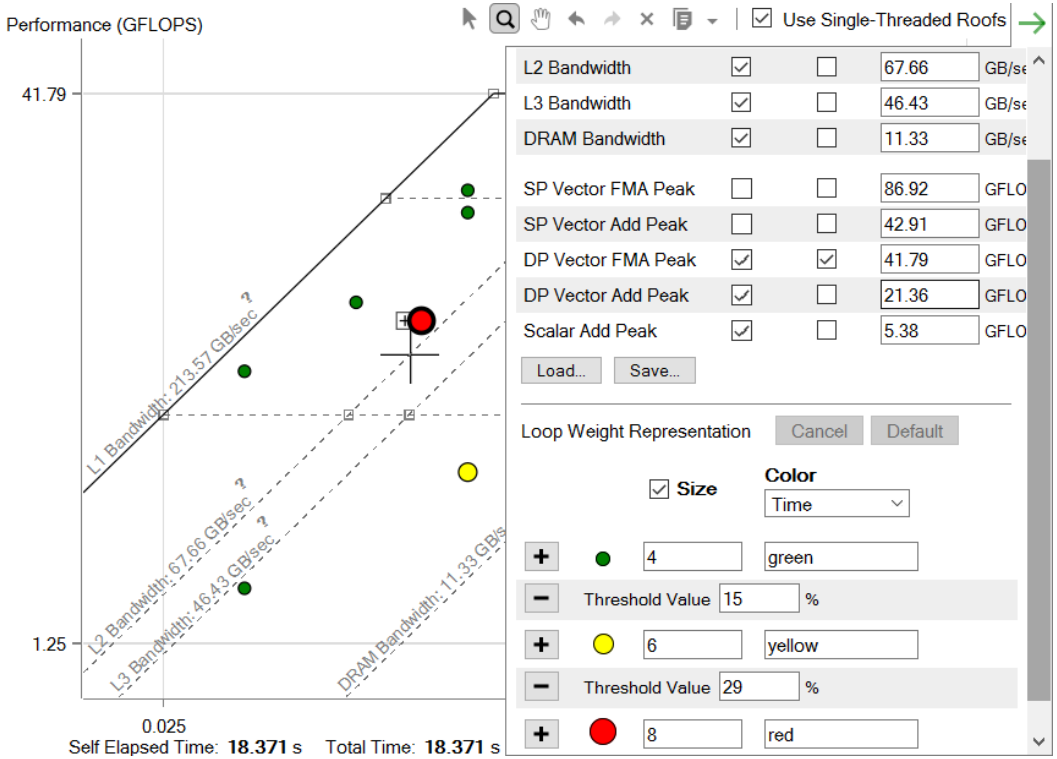


Additional roofs can be plotted for specific computation types or cache levels.

These sub-roofs can be used to help diagnose bottlenecks.

The Intel® Advisor Roofline Interface

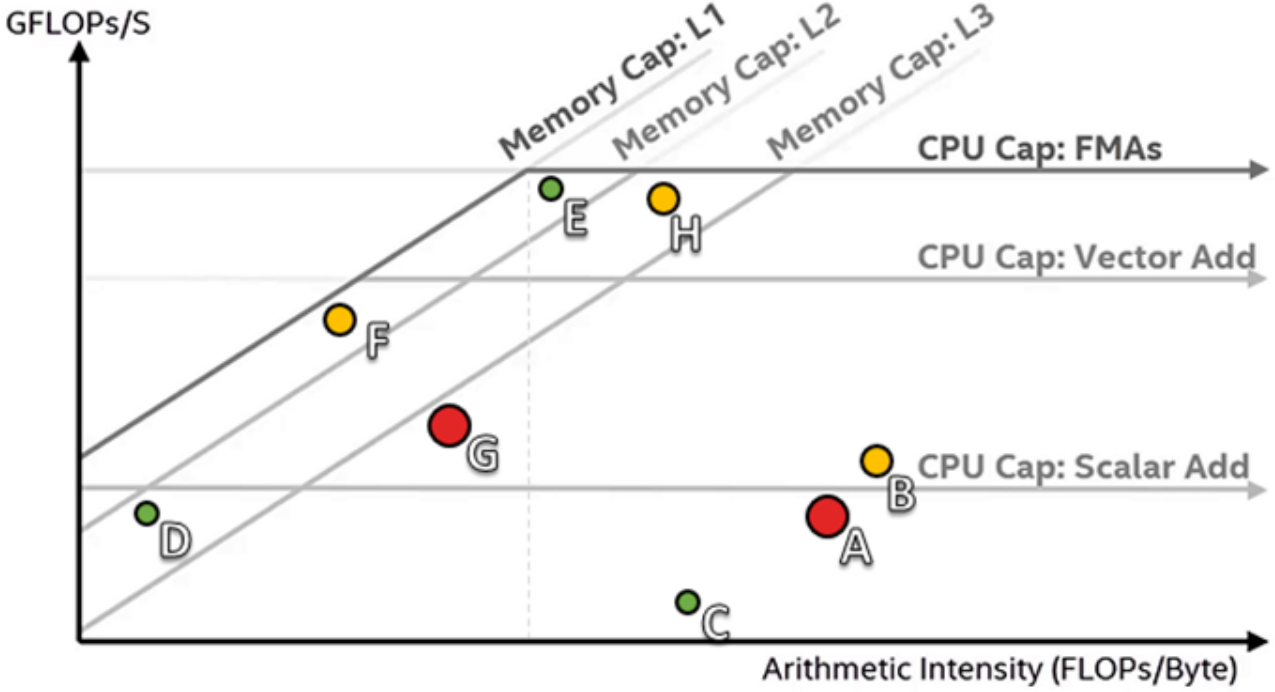
- Roofs are based on benchmarks run before the application.
  - Roofs can be hidden, highlighted, or adjusted.
- Intel® Advisor has size- and color-coding for dots.
  - Color code by duration or vectorization status
  - Categories, cutoffs, and visual style can be modified.



Identifying Good Optimization Candidates

Focus optimization effort where it makes the most difference.

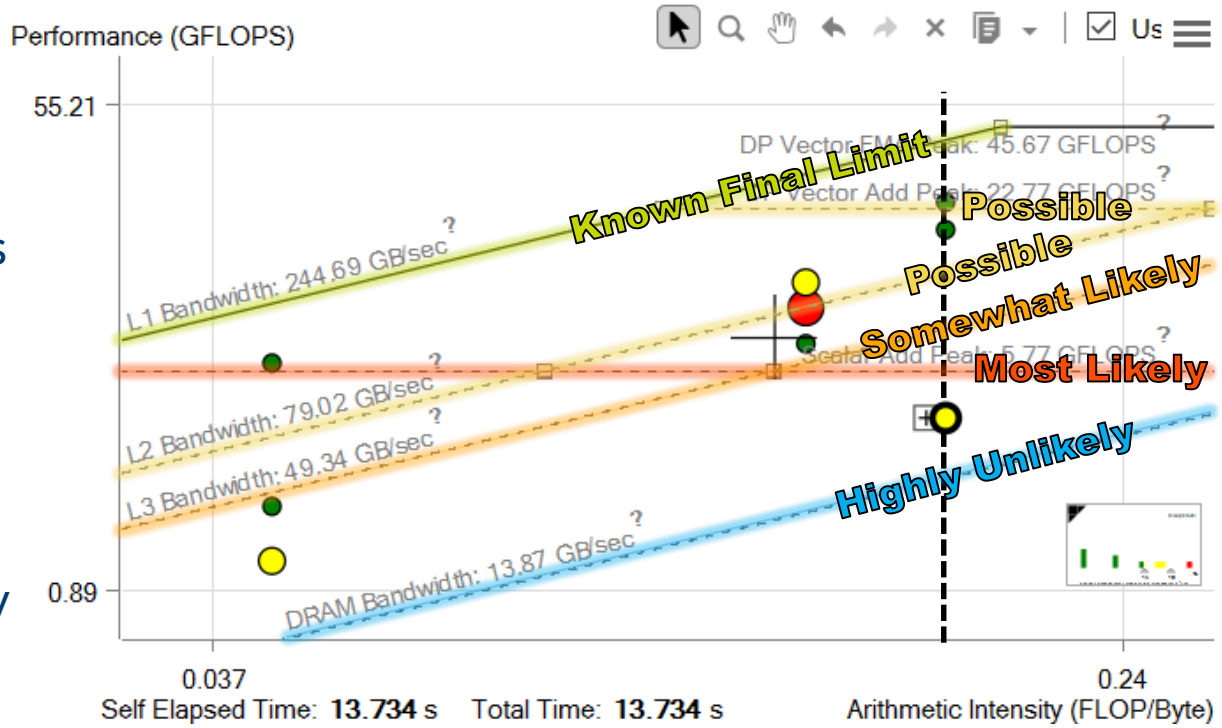
- Large, red loops have the most impact.
- Loops far from the upper roofs have more room to improve.



Identifying Potential Bottlenecks

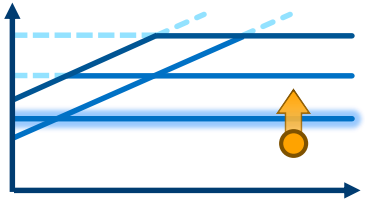
Final roofs *do* apply;
sub-roofs *may* apply.

- Roofs above indicate *potential* bottlenecks
- Closer roofs are the most likely suspects
- Roofs below may contribute but are generally not primary bottlenecks



Back to the example…

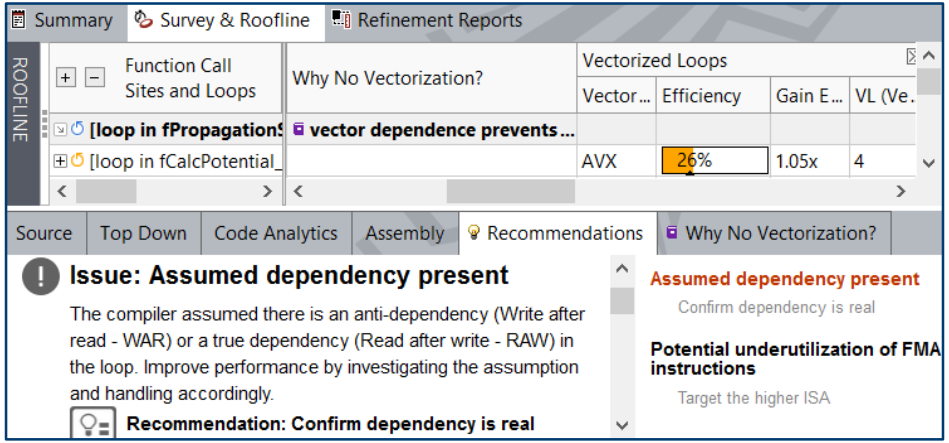
Overcoming the Scalar Add Peak

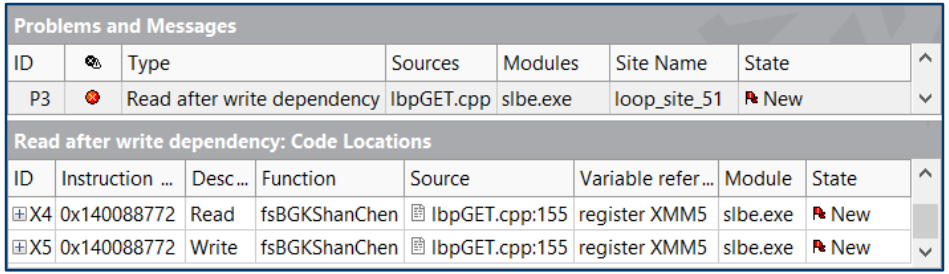


- Survey and Code Analytics tabs indicate vectorization status with colored icons.

  = Scalar = Vectorized

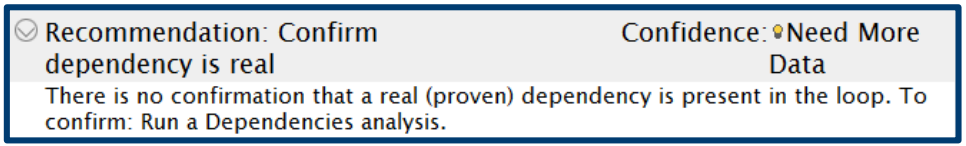
- "Why No Vectorization" tab and column in Survey explain what prevented vectorization.
- Recommendations tab may help you vectorize the loop.
- Dependencies determines if it's safe to force vectorization.



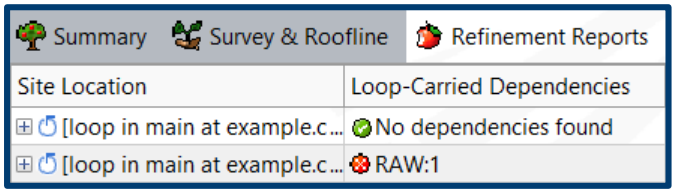


Dependencies Analysis
Vectorization Advisor

- Generally, you don't need to run Dependencies analysis unless Advisor tells you to. It produces recommendations to do so if it detects:
  - Loops that remained unvectorized because the compiler was playing it safe with autovectorization.



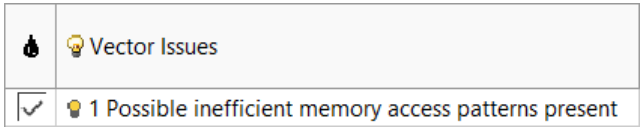
- Use the survey checkboxes to select which loops to analyze.
- If no dependencies are found, it's safe to force vectorization.
- Otherwise, use the reported variable read/write information to see if you can rework the code to eliminate the dependency.



Back to our example…

Memory Access Patterns Analysis
Collecting a MAP

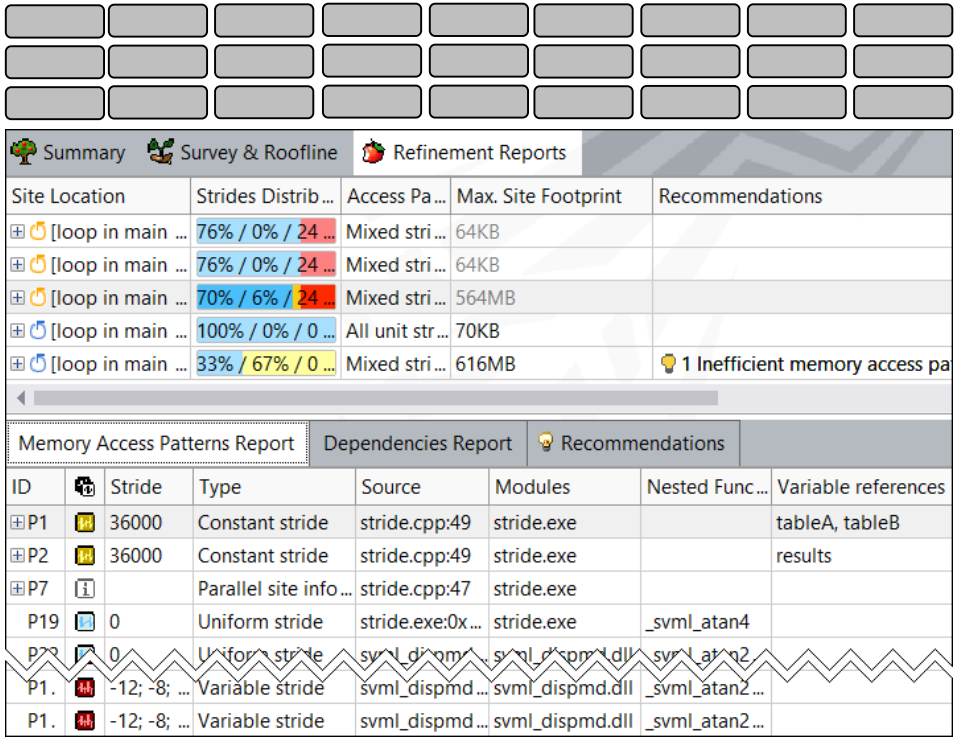
- If you have low vector efficiency, or see that a loop did not vectorize because it was deemed “possible but inefficient”, you may want to run a MAP analysis.
- Advisor will also recommend a MAP analysis if it detects a possible inefficient access pattern.



- Memory access patterns affect vectorization efficiency because they affect how data is loaded into and stored from the vector registers.
- Select the loops you want to run the MAP on using the checkboxes. It may be helpful to reduce the problem size, as MAP only needs to detect patterns, and has high overhead.
  - Note that if changing the problem size requires recompiling, you will need to re-collect the survey before running MAP.

Memory Access Patterns Analysis
Reading a MAP

- MAP is color coded by stride type. From best to worst:
  - **Blue** is unit/uniform (stepping by 1 or 0)
  - **Yellow** is constant (stepping a set distance)
  - **Red** is variable (a changing step distance)
- Click a loop in the top pane to see a detailed report below.
  - The strides that contribute to the loop are broken down in this table.



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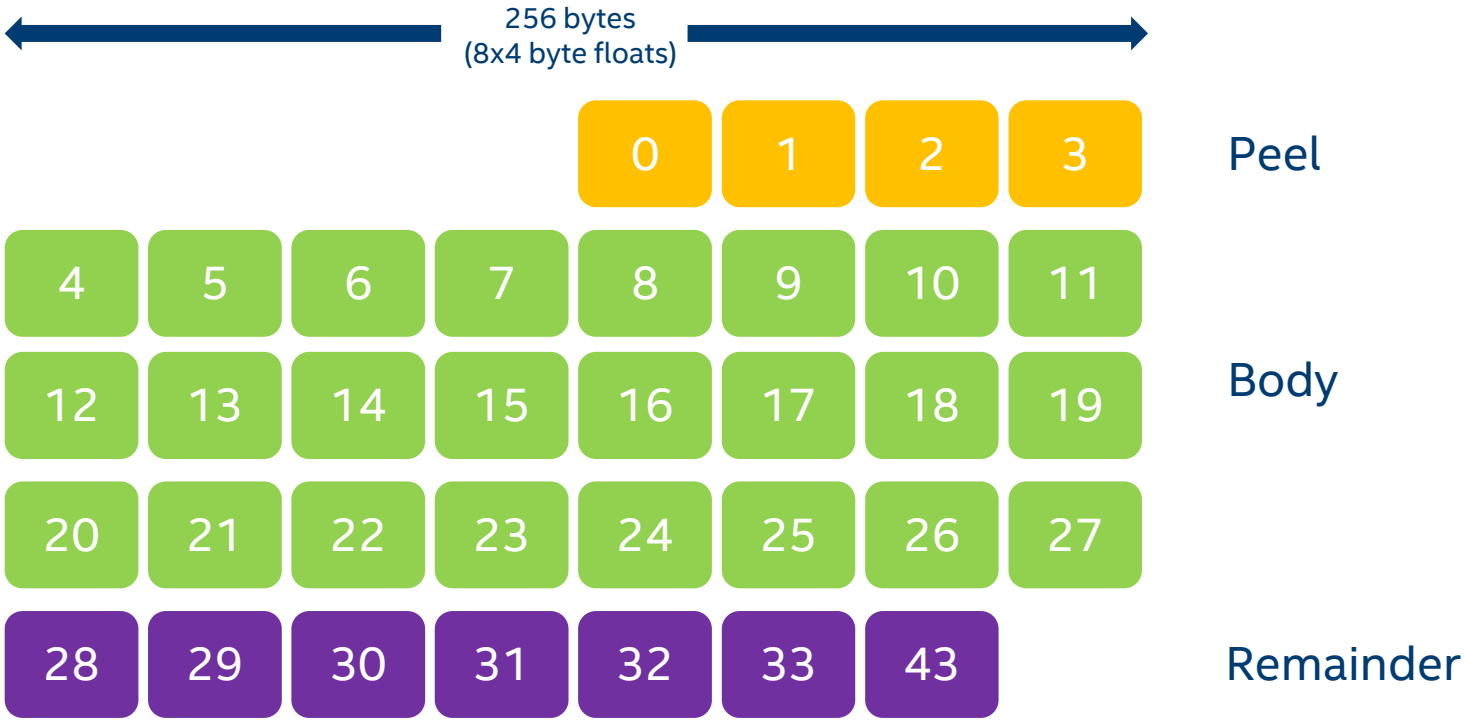
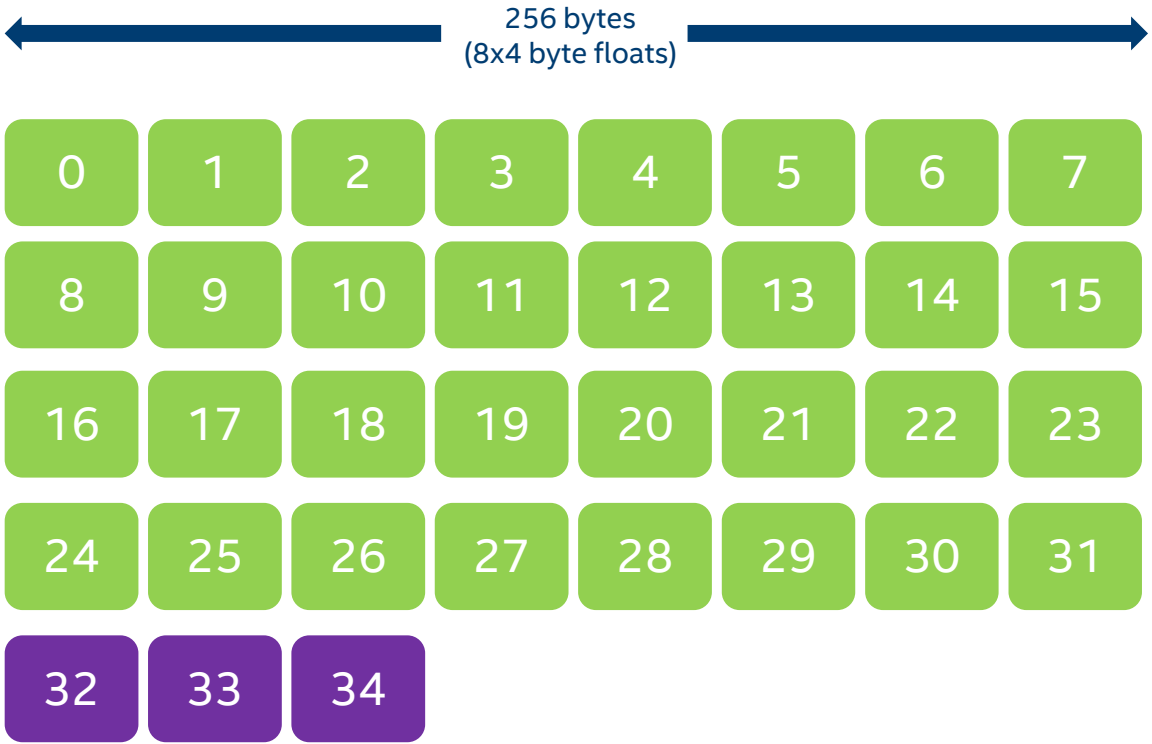
Notice revision #20110804

ALIGNMENT, PADDING AND PEEL/REMAINDER

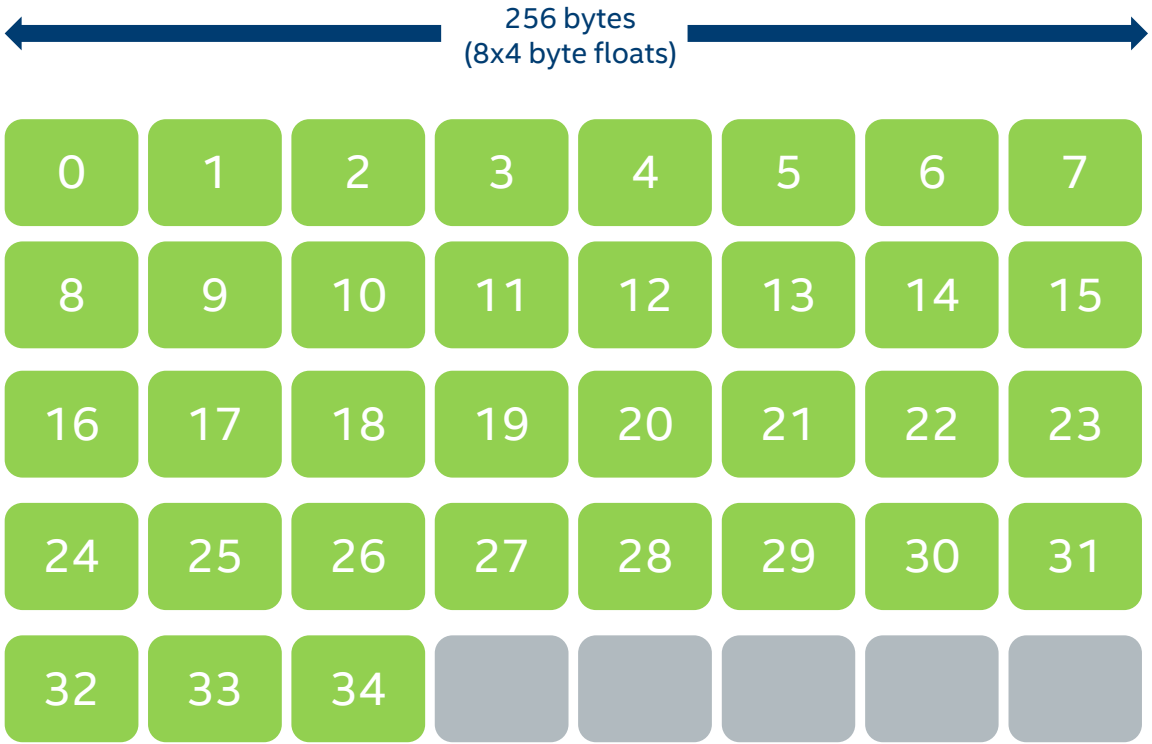
The original 1D table in the peel example



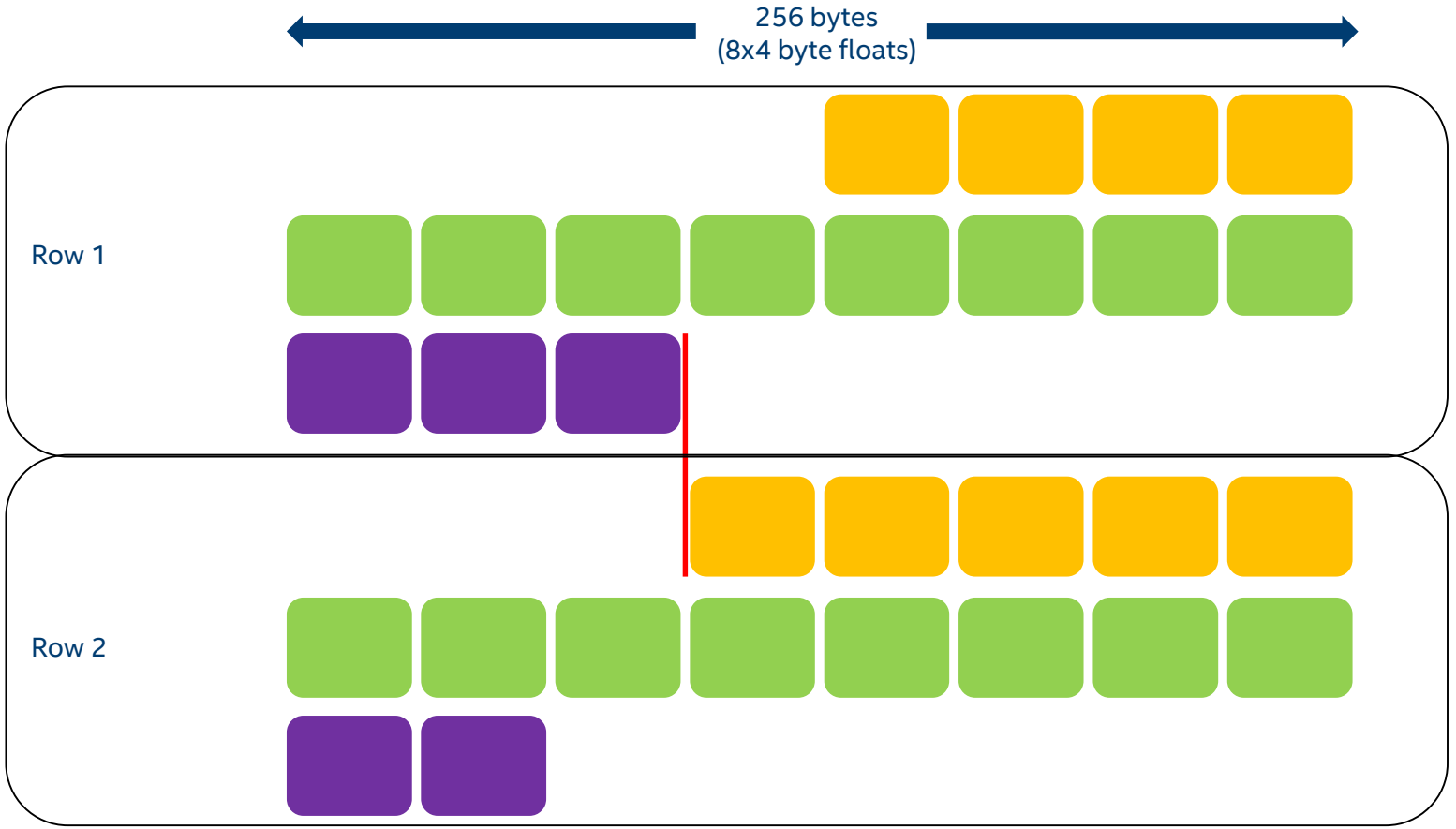
The original 1D table when aligned

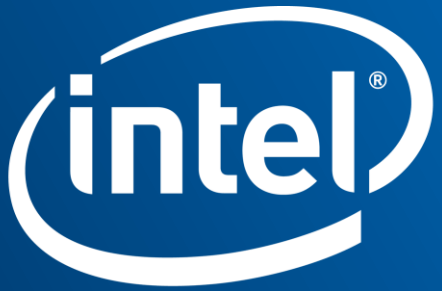


The original 1D table when aligned, padded



The 2D case





Software