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Pulse Sequence Programming using *Pulseq*

Sebastian Littin, Qingping Chen,

Maxim Zaitsev

Division of Medical Physics, Dept. of Radiology,
University Medical Center Freiburg, Germany

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What is a MRI pulse sequence?

- Method to control the MRI scanner
- Way of controlling RF, gradients and ADC
- Strategy to acquire MR signals
- What defines contrast
- …

What is *Pulseq*?

- *Pulseq* is a language to describe MR pulse sequences

- *Pulseq* is the software to generate such pulse sequence descriptions

- *Pulseq* sequences are fixed successions of RF and gradient pulses and ADC events

- *Pulseq* scripts can re-generate *Pulseq* sequences to accommodate user input

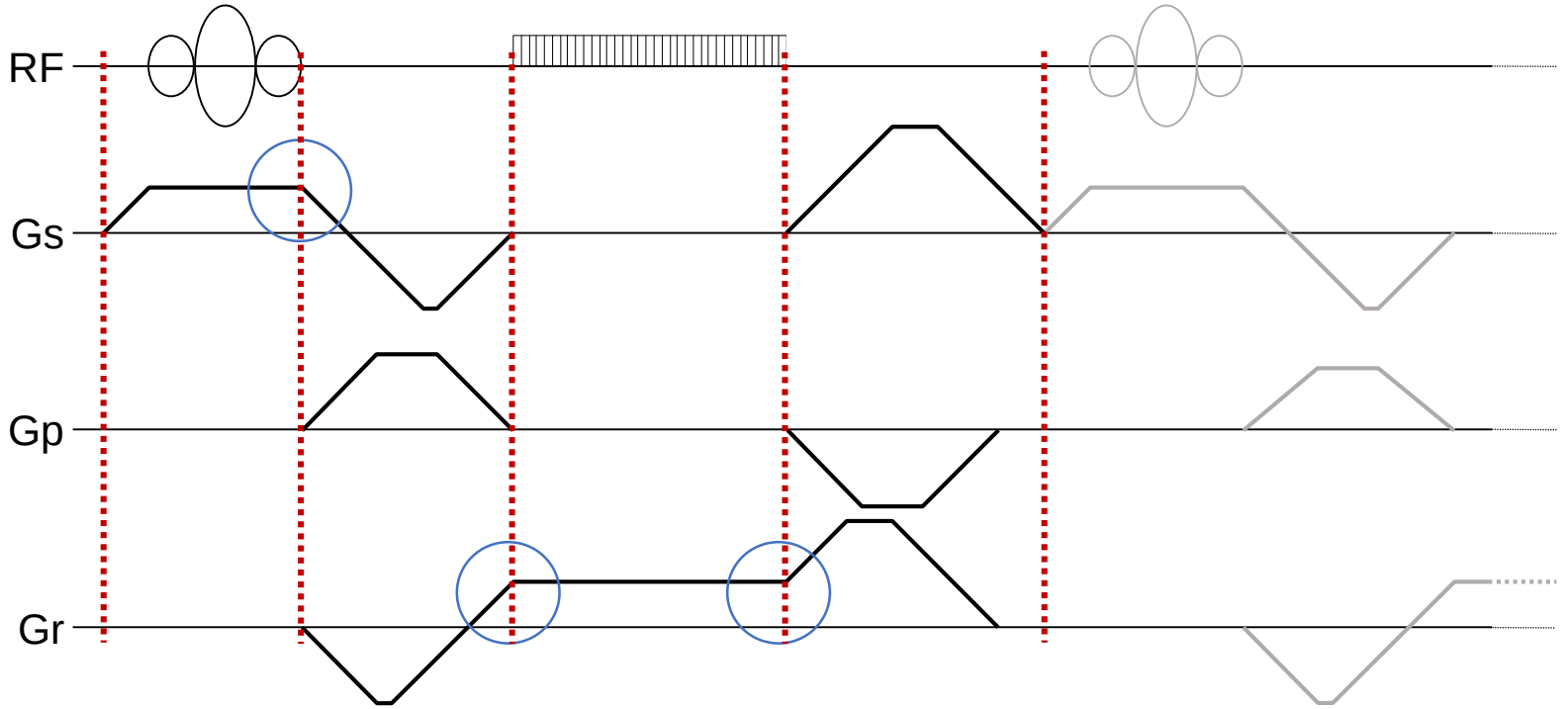
Pulseq ecosystem includes sequences, software to generate them and software and hardware to consume them

Pulseq Philosophy

- Minimize effort for implementation and support on hardware
  - Lean sequence-to-hardware interface
- Remove the thresholds in sequence programming
  - Make simple things truly simple
- Make researcher-oriented features accessible
  - Arbitrary gradients, arbitrary RF, free ordering, X-nuclei, …
- Prevent typical sources of (human) errors
  - Avoid timing errors with “overlapping” gradients
  - Make data flag and counter setting optional/unnecessary
- **Promote open-source thinking, sharing and exchange!**

Image source: wikipedia.org

Pulse sequence definition in *Pulseq*



- Block 1:
  gradient and RF
- Block 2:
  only gradients
- Block 3:
  gradient and ADC
- Block 4:
  only gradients
- Block 5:
  gradient and RF …

- Sequence is a concatenation of non-overlapping blocks
- Gradients do not have to start or end at 0 at the block boundaries

see http://pulseq.github.io/specification.pdf for more details

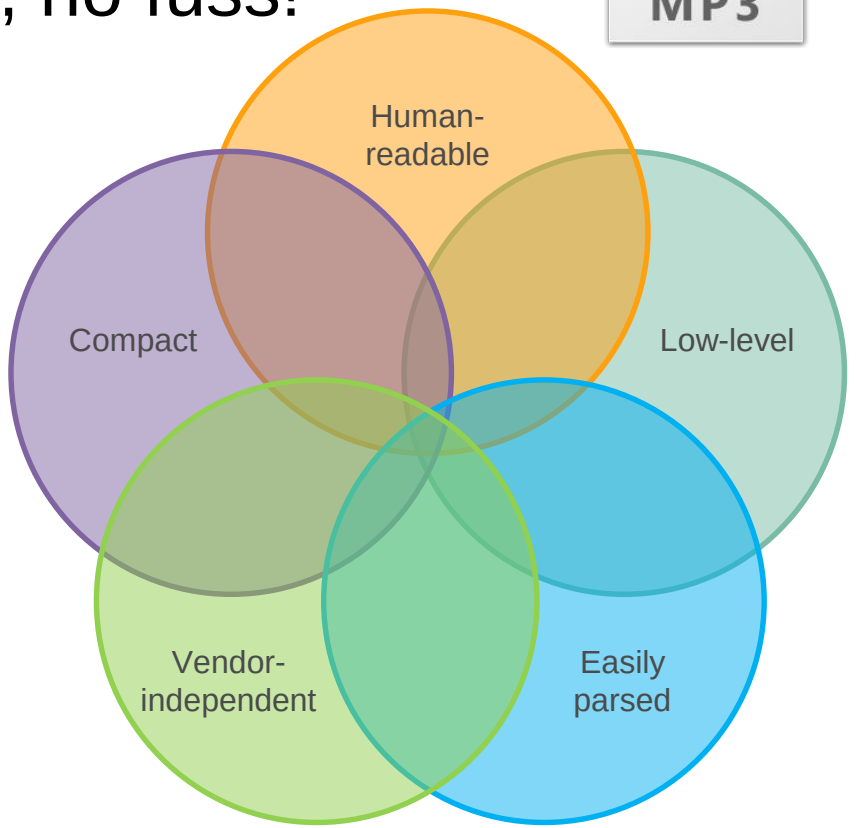
Pulseq block concept in detail

- Each block may contain following events:
  - One optional gradient pulse per axis
  - One optional RF pulse
  - One optional ADC event
- Individual events may define own start delays
- All events in the block overlap in time
- Duration of the block is defined by the longest event
  - Matlab/Python toolboxes use “dummy” delay objects to make blocks longer
- Explicit sequence description
  - No loops, no dependent parameters – like a recorded piece of music!

Pulseq file internals

- Explicit (low level) specification of the pulse sequence
  - Think of an MP3 file (or more precisely lossless FLAC)
- No loops, no parameters, no dependencies, no fuss!

- Text file (human-readable)
  - Simple hierarchy
    (RF pulses, gradients, shapes)
  - Event table keeps it together
  - See http://pulseq.github.io/specification.pdf
    for more details



High-level programming environments

- Matlab *Pulseq* toolbox
- Python *PyPulseq* toolbox

- Further options
  - TOPPE is primarily targeted at GE but can import and export *Pulseq* files
  - GammaStar can export *pulseq* files
  - JEMRIS Bloch simulator can export *pulseq* files
  - CoreMRI Bloch simulator can export *pulseq* files
  - …

Matlab *Pulseq* workflow

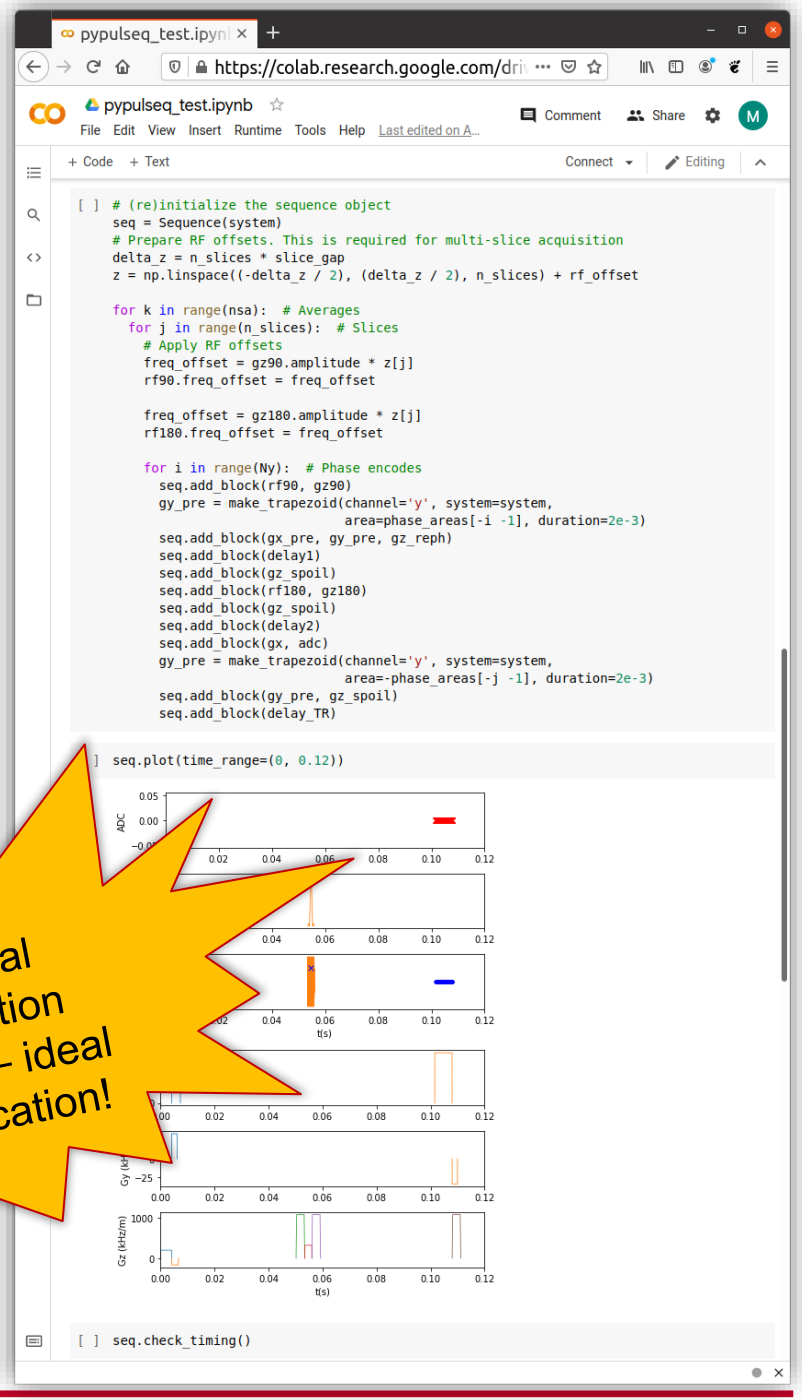
```
system = mr.opts('MaxGrad',30,'GradUnit','mT/m',...
    'MaxSlew',170,'SlewUnit','T/m/s');
seq=mr.Sequence(system);

fov = 220e-3; Nx=64; Ny=64; TE = 10e-3; TR = 20e-3;

[rf, gz] = mr.makeSincPulse(15*pi/180,system,'Duration',4e-3,...
    'SliceThickness',5e-3,'apodization',0.5,'timeBwProduct',4);

gx = mr.makeTrapezoid('x',system,'FlatArea',Nx/fov,'FlatTime',6.4e-3);
adc = mr.makeAdc(Nx,'Duration',gx.flatTime,'Delay',gx.riseTime);
gxPre = mr.makeTrapezoid('x',system,'Area',-gx.area/2,'Duration',2e-3);
gzReph = mr.makeTrapezoid('z',system,'Area',-gz.area/2,'Duration',2e-3);
phaseAreas = ((0:Ny-1)-Ny/2)*1/fov;

delayTE = TE - mr.calcDuration(gxPre) - mr.calcDuration(rf)/2 ...
    - mr.calcDuration(gx)/2;
delayTR = TR - mr.calcDuration(gxPre) - mr.calcDuration(rf) ...
    - mr.calcDuration(gx) - delayTE;
delay1 = mr.makeDelay(delayTE);
delay2 = mr.makeDelay(delayTR);

for i=1:Ny
    seq.addBlock(rf,gz);
    gyPre = mr.makeTrapezoid('y',system,'Area',phaseAreas(i),...
                             'Duration',2e-3);
    seq.addBlock(gxPre,gyPre,gzReph);
    seq.addBlock(delay1);
    seq.addBlock(gx,adc);
    seq.addBlock(delay2)
end

seq.write('gre.seq')
```

a runnable gradient echo sequence code (similar to Siemens' example miniFlash)

- Define the system properties
- Define high-level parameters (convenience)
- Define pulses and ADC objects used in the sequence
- Calculate the delays and reordering tables
- Loop and define sequence blocks
- Duration of each block is defined by the duration of the longest event
- *Copy '*.seq' to the scanner and run it!*

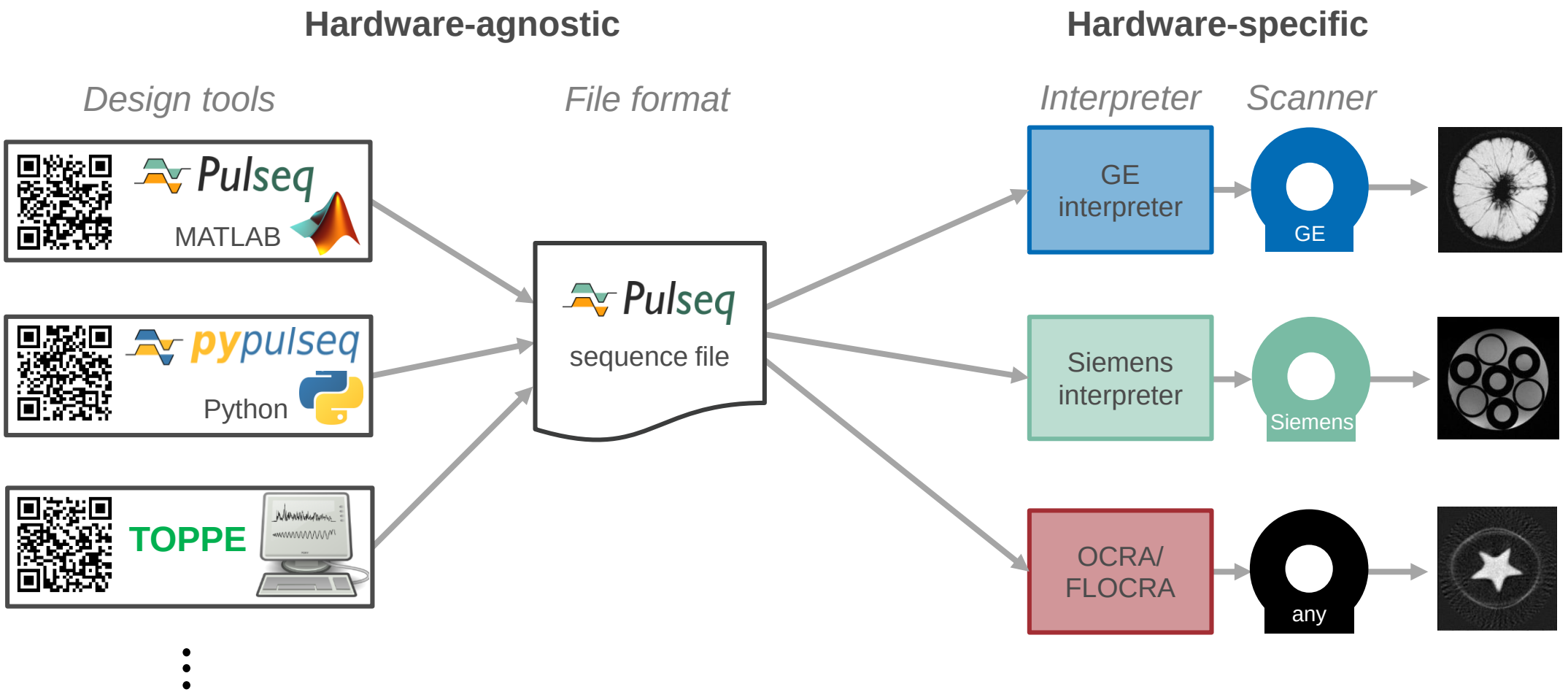
PyPulseq workflow

- ***PyPulseq*** is a close replica of the original Pulseq toolbox that does not require a MATLAB license
- Runs in many Python environments, e.g. as notebook in Jupyter (http://jupyter.org/) or Google Colaboratory
- Workflow:
  - Define the system properties
  - Define high-level parameters (convenience)
  - Define pulses and ADC objects used in the sequence
  - Calculate the delays and reordering tables
  - Loop and define sequence blocks
  - *Download '*.seq' to the scanner and run it!*



No local installation needed – ideal for education!

Pulseq framework overview



Exercises

Go to: www.github.com/pulseq

⇒ Repositories

⇒ Ankara-UMRAM-Hands-on-Course--March-2024

⇒ Tutorials

⇒ Ankara_SplitGREsequence4demo.ipynb

⇒ Open in Colab

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Pulseq MATLAB

pypulseq Python

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