CMOS Pixel Sensor for a Space Radiation Monitor with very low cost, power and mass

Outline:

- Motivations & Specifications
- The first prototype design
- Perspectives

Yang ZHOU, Jérome Baudot, Cyril Duverger, Christine Hu-Guo, Yann Hu, Marc Winter on behalf of PICSEL group, IPHC Strasbourg

yang.zhou@iphc.cnrs.fr

iWoRID 2012 Portugal
Motivations & Specifications

- **Space radiation environment (Medium Earth Orbit)**
  - **Electrons**: 100 keV–7 MeV; $10^4 \rightarrow 10^7$ particles/cm$^2$/s (average number in different orbit)
  - **Protons**: 100 keV–400 MeV; $10^3 \rightarrow 10^4$ particles/cm$^2$/s (average number in different orbit)
  - X rays (negligible in this case); Various heavy ion species (~1%) …

- **Expected space radiation monitor functionalities**
  - **Dosimeter**
    - Measuring the accumulated dose released by those charged particles
  - **Particle Rate Meter**
    - Detect particle flux density with respect to species and energies
    - Alerts in case of very intensive radiation fluxes (e.g. during solar storms)

- **Required features**: low cost (highly miniaturized, low power & mass); real-time information

- **CMOS Pixel Sensor (CPS) used in high energy physics:**
  
  High granularity, Tiny size, large readout speed (~10k Frame/s), Good radiation tolerance (>100k Rad & $10^{12}$neq/cm$^2$), low power consumption (~100mW/cm$^2$)
Motivations & Specifications

How CMOS Pixel Sensor works

- 100% fill-factor
- Miniaturized: sensor and signal processing integrated in the same silicon wafer
- Low cost: standard commercial CMOS technology
- Low power dissipation: rolling shutter operation mode
- Almost dead time free: very short reset time
- Sensitive: signal collected by the sensing diode as low as 200 e⁻ \( ENC \approx 10 e^- \) \( SNR \approx 20 \)
- High granularity

yang.zhou@iphc.cnrs.fr

iWoRID 2012 Portugal 1-5 July 2012
Motivations & Specifications

Why CMOS pixel sensor?

❖ Granularity of pixel sensor: perform like many small detectors
  ❑ High flux detection capability
    Many particles (>100/cm²)/ frame  
    High frame rate (> 10k Hz)  
    Very high counting rate (> 10⁶/cm²/s)
  ❑ Identify particles based on their energy deposition
    Total charge spreads over several pixels  
    Charge measurement for each pixel  
    Sensitivity from single pixel signal  
    Dynamic from clustered pixels signal

❖ CMOS monolithic sensor: smart

  Integrate intelligent digital processing logic → directly give the information we need → real time information possible
Choice of sensor sensitive area, pitch size and readout speed

**Flux estimation:**

- relative uncertainty is:
  \[
  \frac{\sigma_f}{f} = \frac{1}{\sqrt{fST}}
  \]

- Working hypothesis: low cost, miniaturize
  - 10 mm² sensitive area

<table>
<thead>
<tr>
<th>Operation time (T)</th>
<th>Flux $10^3$ part./cm²/s</th>
<th>Flux $10^7$ part./cm²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sigma_f}{f} = 10%$</td>
<td>1 s</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>$\frac{\sigma_f}{f} = 1%$</td>
<td>100 s</td>
<td>10 ms</td>
</tr>
</tbody>
</table>
### Choice of sensor **sensitive area**, **pitch size** and **readout speed**

- Probability of misjudgment by hits pile-up

\[
P(N > N_{\text{MAX}}) = 1 - \sum_{N=0}^{N=N_{\text{MAX}}} \frac{\lambda^N e^{-\lambda}}{N!}
\]

- \(N\): the hits quantity in the same cluster in the same frame
- \(\lambda\): probability of particle hits in the cluster in one frame

<table>
<thead>
<tr>
<th>Frame time (speed)</th>
<th>Pixel pitch</th>
<th>Clusterize in pixels</th>
<th>(P(N \geq 2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (\mu s)</td>
<td>20 (\mu m)</td>
<td>3×3</td>
<td>0.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5×5</td>
<td>0.47%</td>
</tr>
<tr>
<td></td>
<td>50 (\mu m)</td>
<td>3×3</td>
<td>2.18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5×5</td>
<td>13.02%</td>
</tr>
<tr>
<td>50 (\mu s)</td>
<td>50 (\mu m)</td>
<td>3×3</td>
<td>0.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5×5</td>
<td>3.98%</td>
</tr>
<tr>
<td>20 (\mu s)</td>
<td>50 (\mu m)</td>
<td>3×3</td>
<td>0.10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5×5</td>
<td>0.72%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6×6</td>
<td>0.002%</td>
</tr>
</tbody>
</table>

Considering the worst situation:
- \(\text{flux}=10^7\) particles/cm\(^2\)/s for electron
- \(\text{flux}=10^4\) particles/cm\(^2\)/s for proton

\(\leq 20\) hits per frame

**Occupancy \(\leq 10\%\)**

Final choice:
- Area=10 mm\(^2\) pitch= 50 \(\mu m\)
- 64×64 pixels Frame<20 \(\mu s\)
The first prototype design

Device simulation

- 4 steps: translate requirements from measurements → sensor design
  - Geant4: Energy deposited in sensitive area (Monte Carlo simulation)
  - Private model of CPS response: Energy deposited → signal over pixels
  - Digitization of pixel: signal over 3 bits
  - Clusterization algorithm: embedded data processing

3-bit ADC:
LSB: 700 e-; Range: 200e- to 4400e-

Range of expected signal on seed pixel: 300 e- to 120k e-

Noise consideration

Sensor digital performance with vertically impinging

500 keV electron

1 MeV proton
The first prototype design

Device simulation

Energy Loss versus Incident Energy

\[ \theta = 0^\circ \rightarrow 60^\circ \]

Interval containing: 68%, 95% of the values

proton

electron

50 MeV
Clusterization algorithm: embedded data processing

Clusterization

- Sum ADC counts in each cluster
- Store results in each memory (different energy & species particles)

Cluster trimming driven by zeros

Sum of rows: 0 1 5 0 0 20 0 0

Shutter readout row by row

Device simulation

The first prototype design

Perspectives
Device simulation: algorithm performances

The first prototype design

Number of particles which hit the sensor

Depends strongly on the energy distribution of the incoming particles. Low energy particle <10 MeV, large cluster

Number of particles reconstructed

20 particles in a frame with mixed energies (from 1 MeV to 100 MeV)

10% energy resolution
The first prototype design

Front-end readout electronics (1/3): pixel

**Schematic of the pixel**

**Charge to Voltage conversion Factor:**

\[ CVF \approx 60 \mu V/e^- \]

- All NMOS
- Pixel level CDS (correlated double sampling)
- Relative linear response (300 e^-, 10k e^-)
- Enough SNR (Signal to Noise Ratio) for efficiency:
  \[ 300 \ e^- \div 114 \ e^- \approx 21 \]
Front-end readout electronics (2/3): Column level ADC

The dedicated 3-bit successive approximation ADC

- Column level CDS
- Adjustable I/O characteristic
- Special state for reducing power consumption
- Particular layout size: $50 \times 850 \, \text{um}^2$

ADC conversion time = Pixel readout time = 240 ns
The first prototype design

Front-end readout electronics (3/3): layout

0.35 um process, 3.3 V supply voltage

---

**Power dissipation:**
- ~130 uW/pixel
- ~700 uW/ADC with hit
- ~600 uW/ADC without hit
- 64x64 pixel + 64 ADCs: \( \approx 50 \text{ mW} \)

**Timing**
- One row: 240 ns
- One frame (32 rows): 7.68 \( \mu \text{s} \)
**Perspectives**

- **2012-2013**
  - Reception of 1st prototype at mid-september 2012
  - Test
  - Design of Clusterization & Hit counting logic

- **End of 2013: 1st full validated architecture**
  - Weight: few grams
  - Size: $5 \times 15$ mm$^2$ (estimated)
  - Measurement: $10^3-10^7$ part./cm$^2$/s with 10% relative uncertainty in 1 second
  - $e^-$ & $p^+$ separated up to 50 MeV

Additional $e^-/p^+$ separation can be achieved using several sensors with different shieldings

**Application would not be limited in space radiation detection**

---

**Floor plan of the future final smart sensor**

---

**M... & S... The first prototype design**

---

**iWoRID 2012**

---

**14 Yang.Zhou@iphc.cnrs.fr**

---

**Portugal 1-5 July 2012**
Thank you for your attention
Backup Slides
Those effects which do exist but negligible (1/2)

X ray

GOES X-ray satellite data (35,800 km above the Earth)

GOES X-ray Flux (5 minute data)

Watts m\(^{-2}\)

10\(^{-9}\) 10\(^{-8}\) 10\(^{-7}\) 10\(^{-6}\) 10\(^{-5}\) 10\(^{-4}\) 10\(^{-3}\)

Universal Time

Updated 2011 Oct 26 16:30:12 UTC
NOAA/SWPC Boulder, CO, USA

Only hard X-ray: 0.1 A – 1 A (12 keV – 120 keV) can penetrate our shielding

The average flux reach our sensor:

\[ 10^{-9} \text{watts/m}^2 \]

Considering the efficiency of 62.5 keV X-ray in our sensor is lower than 1%, that means every 100 seconds we have a chance that X-ray deposit 62.5 keV energy in our sensor. That is quite small.

\[ 10^{-14} \text{J/s in the sensor's sensitive area} \]

\[ 10^{-14} / (1.6 \times 10^{-19}) = 62.5 \text{ keV/s} \]
Those effects which do exist but negligible (2/2)

- **Proton nuclear reaction (rare)**
  
  depends on the energy and range. Still do not have exact data to support, but the probability would be less than 1%.

- **Various heavy ion species (~1%)**


*A.B. Rosenfeld, et al. *A New Silicon Detector for Microdosimetry Applications in Proton Therapy*, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 47, NO. 4, AUGUST 2000
Private model of CPS response

- Stopping power from NIST*

* NIST: National Institute of Standards and Technology USA
* PSF: Point Spread Function; was generated from the test results of MIMOSA 5, 17, 18, 22, 24 and LUCY with the same collecting diode size.

Double Gaussian PSF*

\[
\frac{1}{2\pi} \left[ p \frac{1}{\sigma_1^2} \exp \left(-\frac{x^2 + y^2}{2\sigma_1^2}\right) + \frac{1-p}{\sigma_2^2} \exp \left(-\frac{x^2 + y^2}{2\sigma_2^2}\right) \right] \times \alpha
\]

Where \( x \) and \( y \) is the distance between collecting diode and generated e- in \( x \) and \( y \) direction; \( p \) is the proportion of the double Gaussian; \( \sigma_1 \) and \( \sigma_2 \) is the standard deviation of the Gaussian function; \( \alpha \) is the modified coefficient which depends on the pitch size.

- Model independent of “Z” dimension
  - But able to deal with tracks having \( \theta \neq 0 \)

Averagely divided the range into 14 sections.

**Total charge collected on a diode**

\[
\sum_{i=1}^{14} \frac{S_i}{3.6} \times PSF
\]
Device simulation

Digital signal of 5x5 cluster VS energy of incident particles

Interval containing: 68%, 95% and 99% of the values

Left: $\theta = 60^\circ$
Right: $\theta = 0^\circ$

- Electron
- Proton

Cluster ADC counts

Incident particle energy (MeV)
Shielding: could help a lot

Add shielding

**Side shielding:** limit particles’ incident angle
- have a better particle energy and species resolution
- Obtain directional resolution for the anisotropic flux environment

**Front shielding:**
- Protect the sensor from sunlight
- Protect the sensor from extreme radiation dose

**Back shielding:**
Satellite itself may help shield the back

**Material and thickness of the shielding:**

*Aluminum:* spacecraft structural enclosures are typically a few millimeters thick and normally composed of aluminum;

- 0.7 mm aluminum can shield $e^{-} < 0.5$ MeV and $p < 10$ MeV
- 2 mm aluminum can shield $e^{-} < 1.5$ MeV and $p < 20$ MeV
Trends of detectors for space application

- **Geiger counter** (Omni-detector)

- **SEM** (space environment monitor)

- **SREM** (standard radiation environment monitor)
  - electron > 0.5 MeV; proton > 10 MeV; angular resolution 20°

- **MRM** (miniaturized radiation monitor): Two parallel activities
  - CCD pinhole (*Matra Bae, UK*)
  - Scintillating fibre (*Sensys, NL*)

- **Future...** ubiquitous presence in space will require

  *Overcome all the challenges*

  *Real time data; high flux; full energy range; accuracy; miniature; low cost;*
Existing technology: Miniature Radiation Monitor

- Power consumption < 105mW at 12V DC.
- Total mass 397g (electronics plus probe).
- Dimension 85mmX65mmX60mm.
- Detect: 1MeV gamma, 50-300MeV protons, 3MeV beta and various heavy ion species at 66 to 176MeV.

*www.esa-spaceweather.net/spweather/workshops/...w1/ali51.pdf

**Order of magnitude reduction in mass, volume, power and cost budgets**

The thin outer coating of low-Z (low density) material is a precaution against excessive bremsstrahlung generation

✓ Double-conical pinhole aperture
✓ Different thickness local shielding

Design details: Pixel

- Reset structure:
  recover quickly from large signal;
- Input dynamic range:
  Relative linear response: 200 e\textsuperscript{-} to 10000 e\textsuperscript{-} ;
  Nonlinear response: 10000 e\textsuperscript{-} to 50000 e\textsuperscript{-} ;
  Saturate: higher than 50000 e\textsuperscript{-} ;
- Enough SNR for efficiency:
  300 e\textsuperscript{-} /14 e\textsuperscript{-} = 21

Timing diagram: 240 ns for reading one pixel
The dedicated 3-bit successive approximation ADC

- Adjustable I/O characteristic;
- Extra decision state to reduce power consumption;
- 30 ns for one comparison, 240 ns for a complete conversion

**Input/output characteristic of the 3-bit ADC**
The chip works in rolling shutter operation mode.
<table>
<thead>
<tr>
<th><strong>Post-simulation results of ADC</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
</tr>
<tr>
<td><strong>Conversion time</strong></td>
</tr>
<tr>
<td><strong>Resolution (LSB)</strong></td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Gain error</strong></td>
</tr>
<tr>
<td><strong>Sampling rate</strong></td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Bandwidth(-3dB)</td>
</tr>
<tr>
<td>Gain</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Offset</th>
<th>1.6 mV (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2 mV (std dev)</td>
</tr>
<tr>
<td>Response time</td>
<td>4 ns</td>
</tr>
</tbody>
</table>
Simulation results of pixel (200 e- input)

Monte carlo simulation (mismatch + process)

Mean = 13.9 mV
Sd = 2.33 mV

Transient noise simulation

Mean = 12.04 mV
RMS = 0.83 mV

Entries = 400
Mean = 12.04 mV
RMS = 0.83 mV
Bin = 50
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Sum

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
0 0 0 0 0 0 0 0
0 1 1 0 0 0 0 0
0 1 5 0 0 0 0 0
0 0 0 0 0 1 0 0
0 0 0 0 1 5 1 0
0 0 0 0 1 7 2 0
0 0 0 0 0 1 1 0
0 0 0 0 0 0 0 0

Sum

0 0 0 0 1 8 3 0
<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Trim

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
Sum

0 0 0 0 2 13 4 0
Cluster Q=20

Cluster end detected

Trim

+2
+4

yang.zhou@iphc.cnrs.fr
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Sum

0 0 0 0 0 0 0 0
<table>
<thead>
<tr>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Trim

| 0 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Trim
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Trim Cluster end detected

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Trim +2

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Sum

0 0 0 0 0 0 0 0