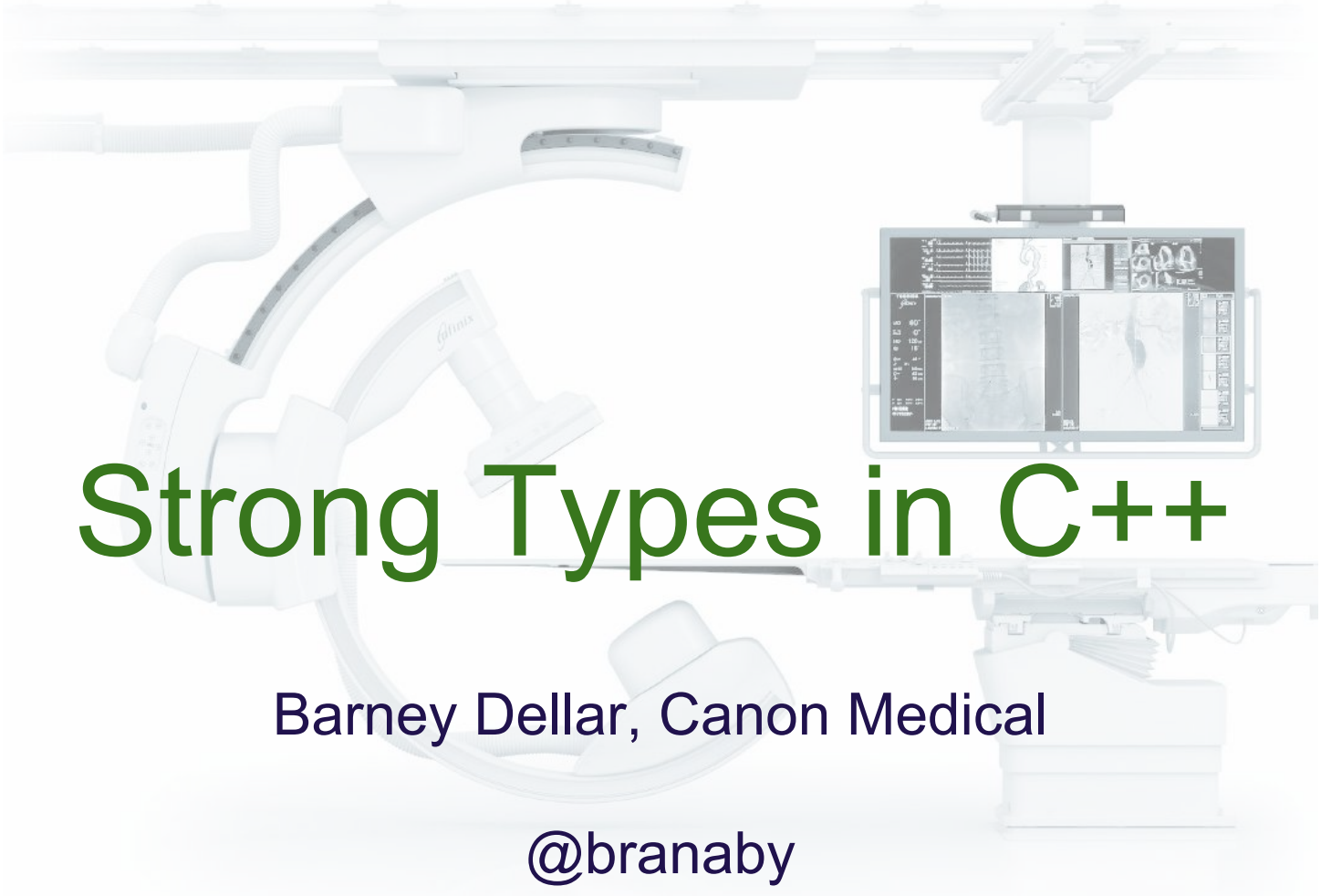


Strong Types in C++

Barney Dellar, Canon Medical

@branaby

So, what is a strong type??

What is a type??

What is a type??

What is a type??

What is a type??

JavaScript

```
let x = 5;
x = 'five';
x = 5.0;
```

```
const separateByComma = function (a, b) {
    return a + ', ' + b;
};

console.log(separateByComma('x', 'y'));
```

```
const separateByComma = function (a, b) {
    return a + ', ' + b;
};

console.log(separateByComma('x', 'y'));

// Prints "x, y"
```

```
const separateByComma = function (a, b) {
    return a + ', ' + b;
};

console.log(separateByComma(1, 2));
```

```
const separateByComma = function (a, b) {
    return a + ', ' + b;
};

console.log(separateByComma(1, 2));

// Prints "1, 2"
```

```
x = 5

x = 'five'

x = 5.0
```

```
def separate_by_comma(a, b):
    return a + ', ' + b


print(separate_by_comma('x', 'y'))
```

```
def separate_by_comma(a, b):
    return a + ', ' + b

print(separate_by_comma('x', 'y'))

# prints "x, y"
```

```
def separate_by_comma(a, b):
    return a + ', ' + b


print(separate_by_comma(1, 2))
```

```
Traceback (most recent call last):
  File "C:\Users\bpde\Desktop\test.py", line 6, in <module>
    print(separate_by_comma(1, 2))
  File "C:\Users\bpde\Desktop\test.py", line 2, in
separate_by_comma
    return s1 + ', ' + s2
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

```
Traceback (most recent call last):
  File "C:\Users\bpde\Desktop\test.py", line 6, in <module>
    print(separate_by_comma(1, 2))
  File "C:\Users\bpde\Desktop\test.py", line 2, in
separate_by_comma
    return s1 + ', ' + s2
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

```
Traceback (most recent call last):
  File "C:\Users\bpde\Desktop\test.py", line 6, in <module>
    print(separate_by_comma(1, 2))
  File "C:\Users\bpde\Desktop\test.py", line 2, in
separate_by_comma
    return s1 + ', ' + s2
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

```
Traceback (most recent call last):
  File "C:\Users\bpde\Desktop\test.py", line 6, in <module>
    print(separate_by_comma(1, 2))
  File "C:\Users\bpde\Desktop\test.py", line 2, in
separate_by_comma
    return s1 + ', ' + s2
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

```
Traceback (most recent call last):
  File "C:\Users\bpde\Desktop\test.py", line 6, in <module>
    print(separate_by_comma(1, 2))
  File "C:\Users\bpde\Desktop\test.py", line 2, in
separate_by_comma
    return s1 + ', ' + s2
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

```
std::string SeparateByComma(std::string a, std::string b) {
    return a + ", " + b;
}

std::cout << SeparateByComma("x", "y");
```

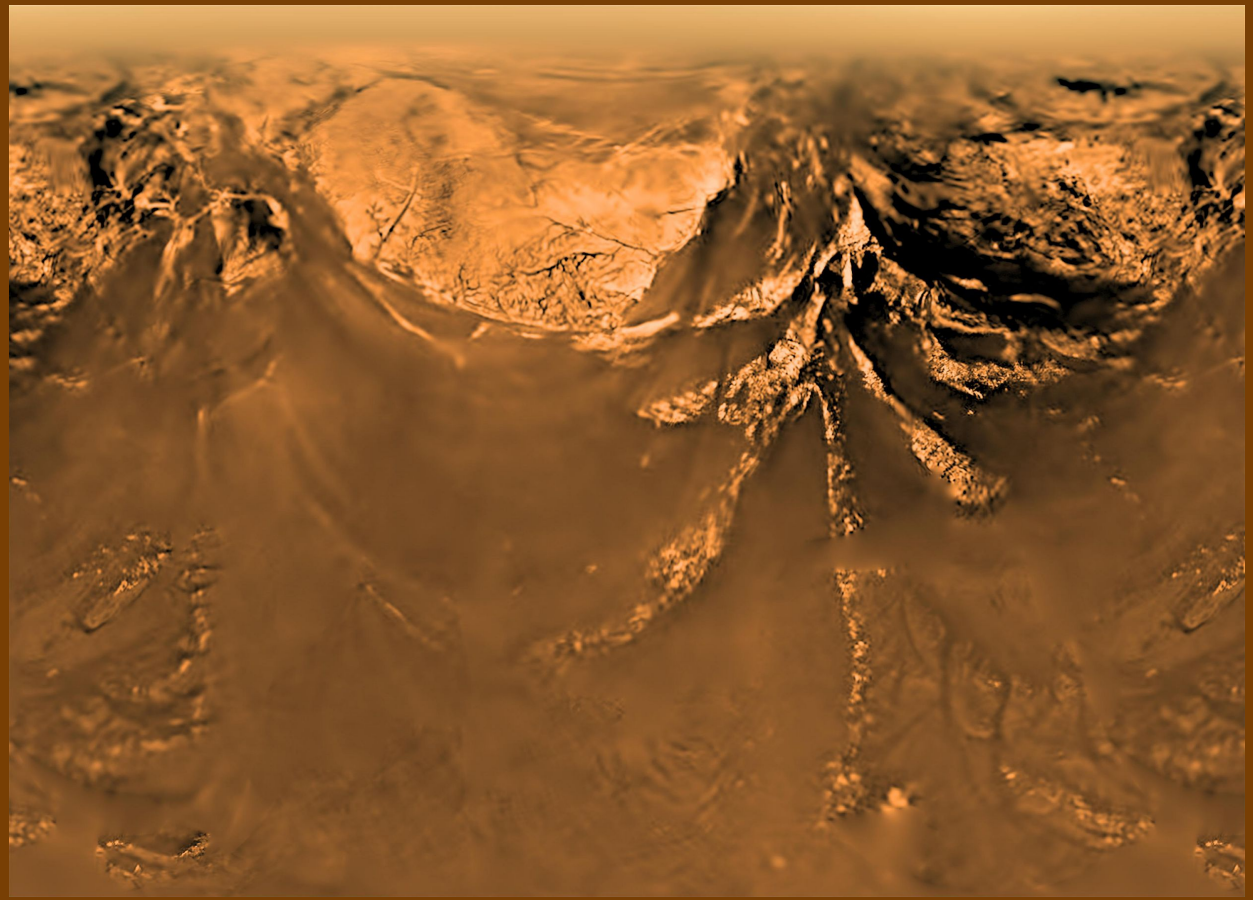
```
std::string SeparateByComma(std::string a, std::string b) {
    return a + ", " + b;
}

std::cout << SeparateByComma("x", "y");

// Prints "x, y"
```

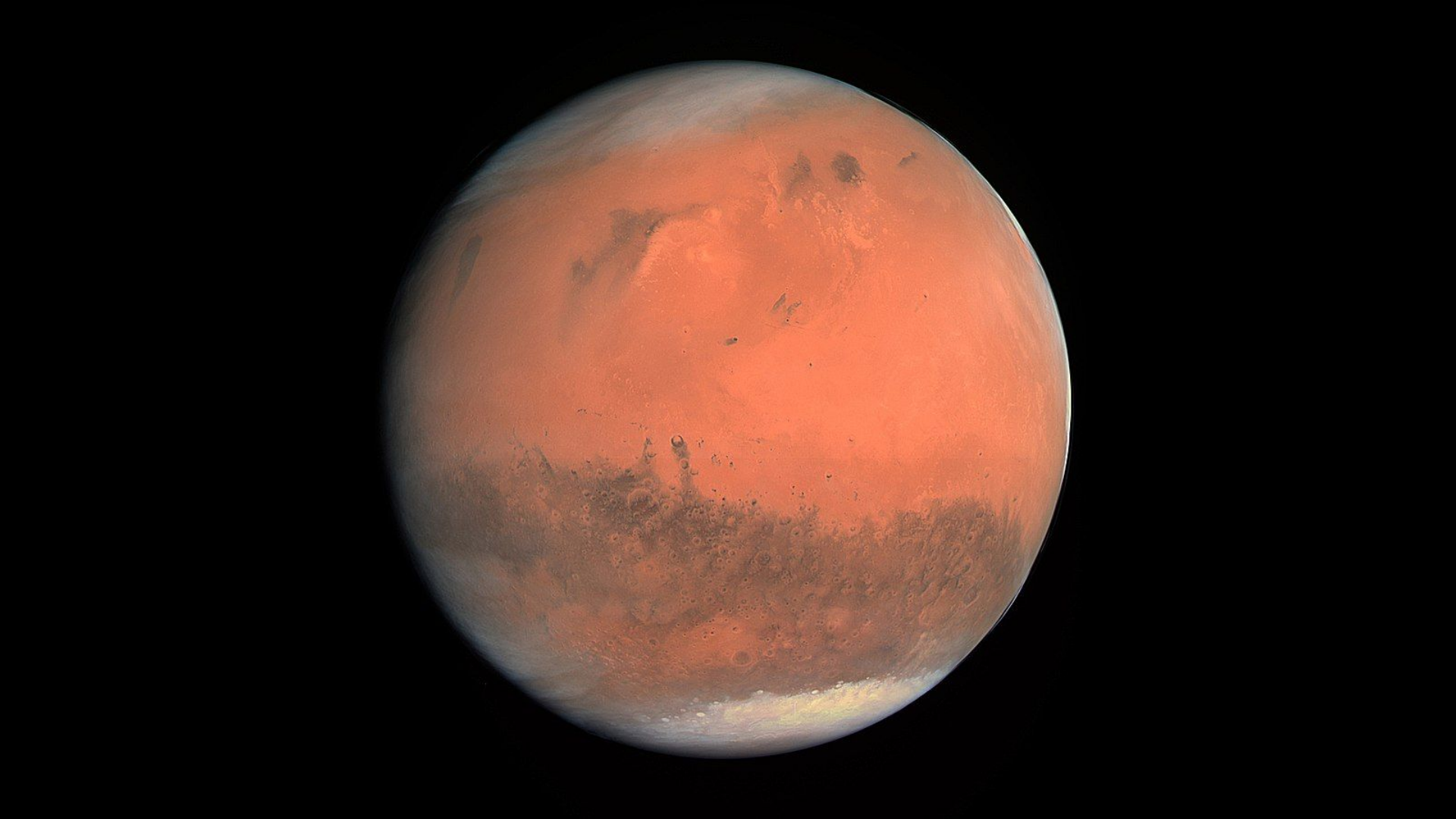
```
std::string SeparateByComma(std::string a, std::string b) {
    return a + ", " + b;
}

std::cout << SeparateByComma(1, 2);
```

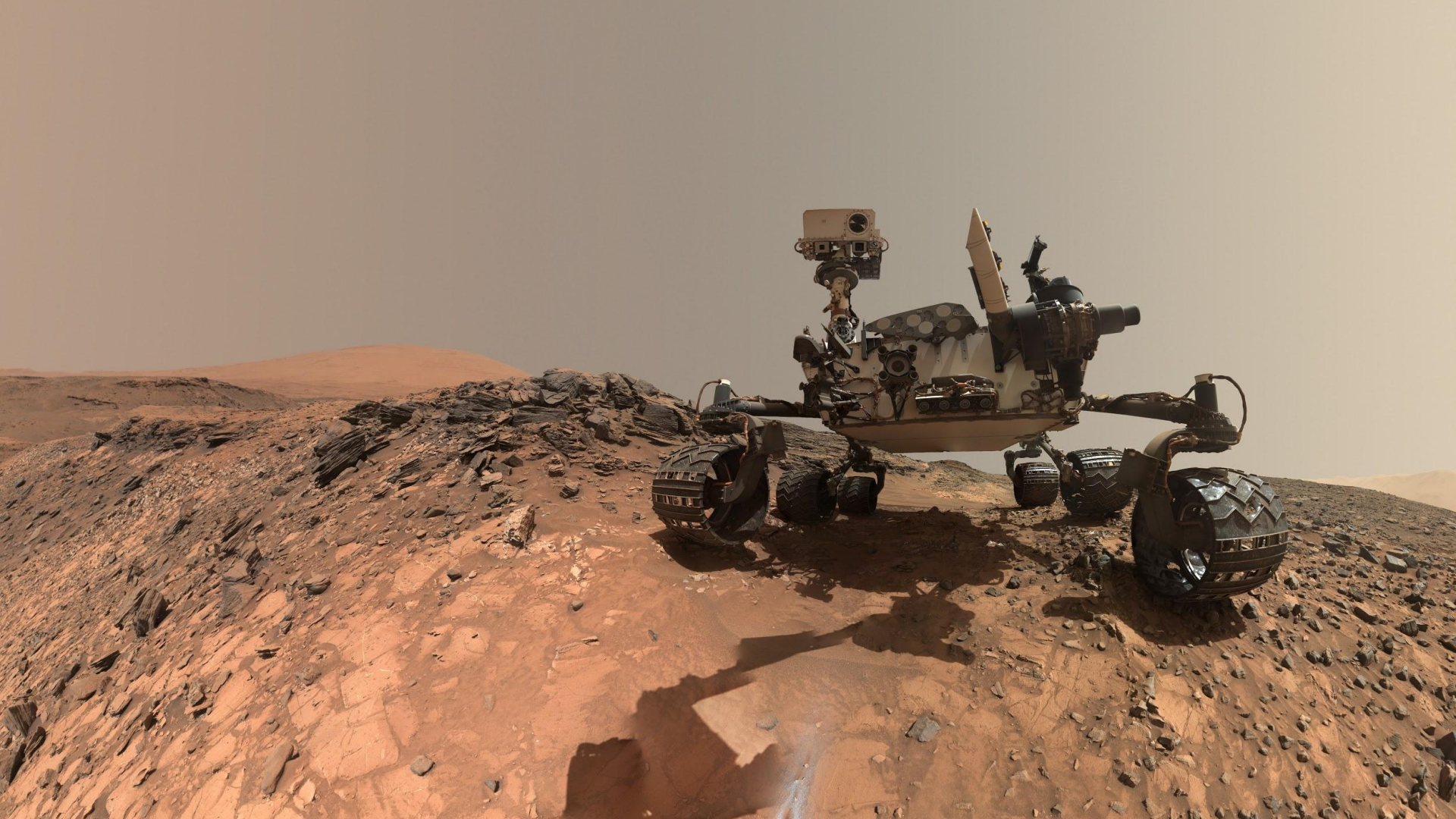
```
error C2664: 'std::string
SeparateByComma(std::string,std::string)': cannot
convert argument 1 from 'int' to 'std::string'
```

C++ is Strongly Typed :-)

C++ is Strongly Typed :-)







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ESA, INAF. Graphic rendering by Davide Coero Borga – Media INAF

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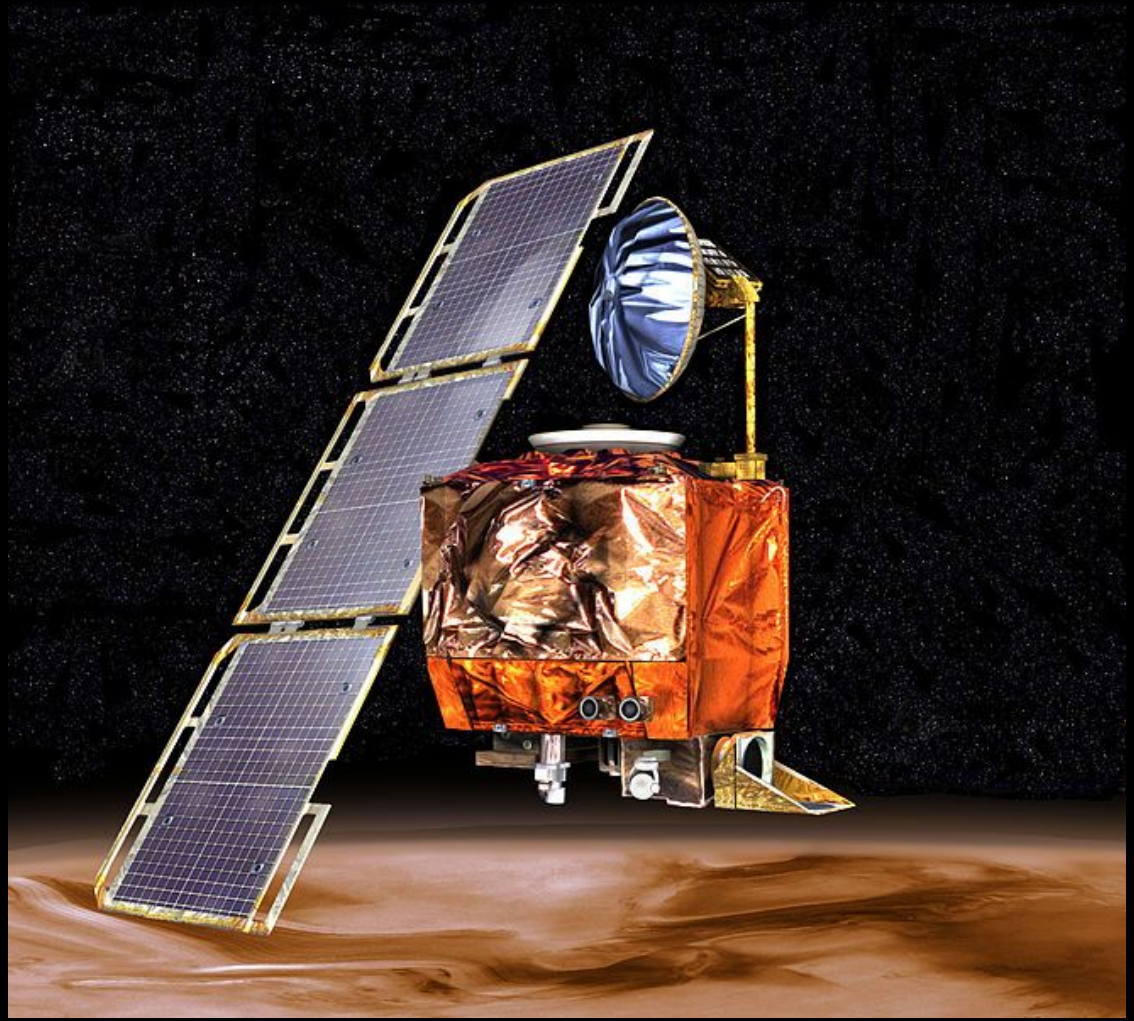
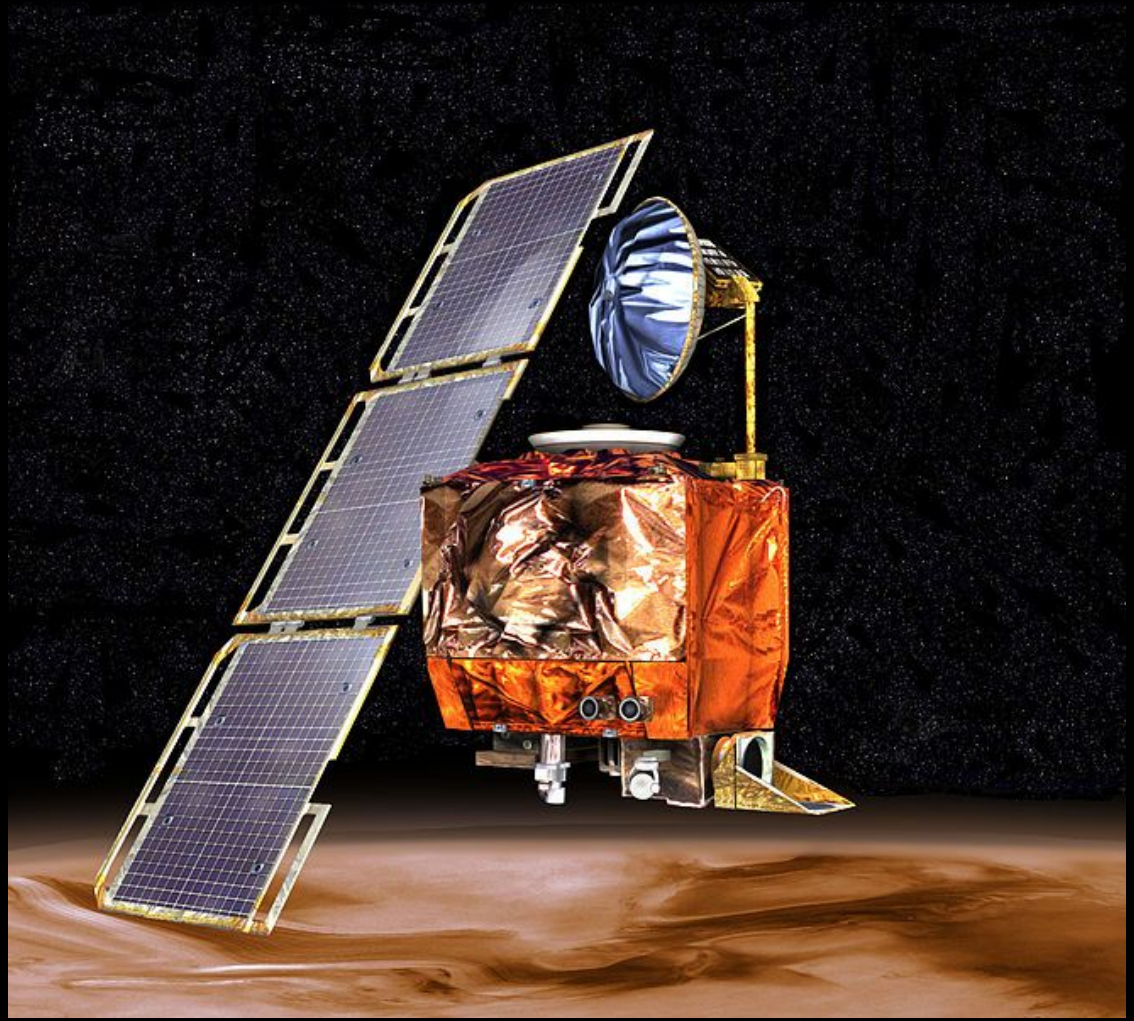
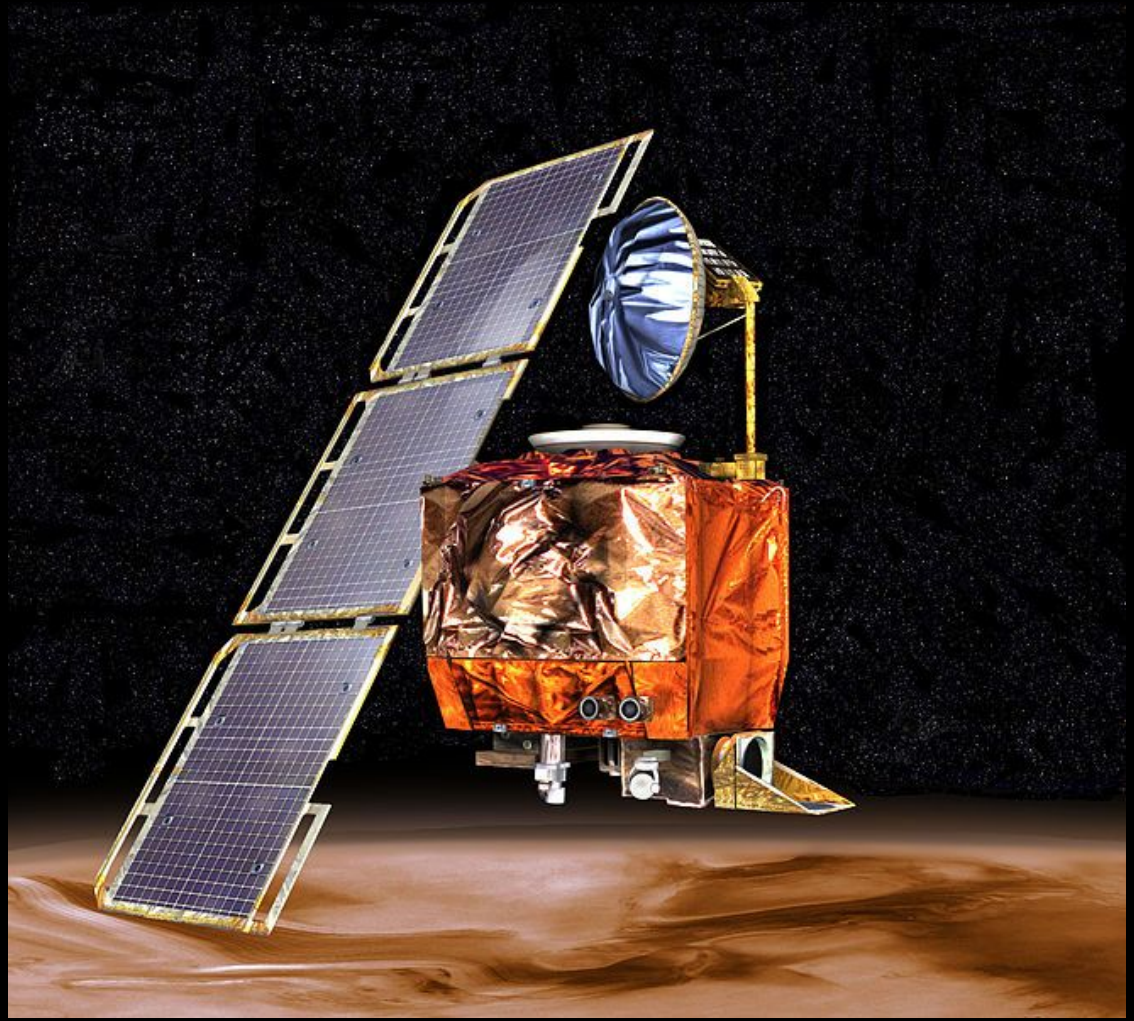




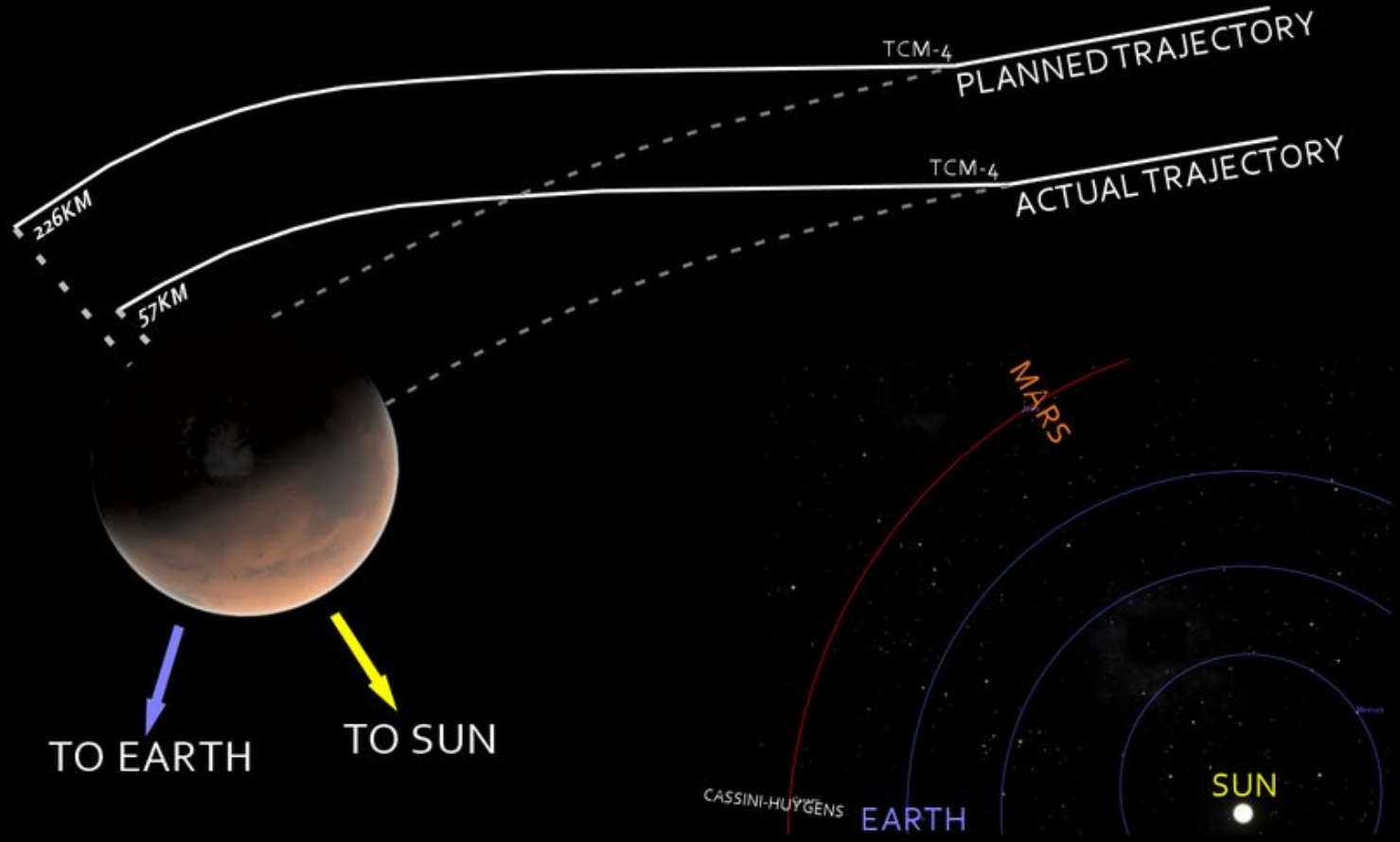


“Metric system used by NASA for many years”

“Metric system used by NASA for many years”

```
// Not actual Lockheed Martin code
double Impulse()
{
    ...
    return impulseInPoundForceSeconds;
}

// Not actual NASA code
double impulseInNewtonSeconds = Impulse();
double CalculateAngularMomentumDesaturation(impulseInNewtonSeconds);
```


TCM-4
PLANNED TRAJECTORY
TCM-4
ACTUAL TRAJECTORY
226KM
57KM
TO EARTH
TO SUN
MARS
CASSINI-HUYGENS
EARTH
SUN

```
// Not actual Lockheed Martin code
double Impulse()
{
    ...
    return impulseInPoundForceSeconds;
}

// Not actual NASA code
double impulseInNewtonSeconds = Impulse();
double CalculateAngularMomentumDesaturation(impulseInNewtonSeconds);
```

```
// Not actual Lockheed Martin code
double Impulse()
{
    ...
    return impulseInPoundForceSeconds;
}

// Not actual NASA code
double impulseInNewtonSeconds = Impulse();
double CalculateAngularMomentumDesaturation(impulseInNewtonSeconds);
```

```
// Not actual Lockheed Martin code
double Impulse()
{
    ...
    return impulseInPoundForceSeconds;
}

// Not actual NASA code
double impulseInNewtonSeconds = Impulse();
double CalculateAngularMomentumDesaturation(impulseInNewtonSeconds);
```

Types as meaning

Types as meaning

Types as meaning

```
double CalculateForce(double mass);
```

```
double CalculateForce(double mass);
```

```
Newton CalculateForce(Kilogram mass);
```

```
Newton CalculateForce(Kilogram mass);

Pound mass = GetMass();
PoundForce force = CalculateForce(mass); // Error!
```

Kilogram	floating point number
Pound	floating point number
Newton	floating point number
PoundForce	floating point number

```
using Kilogram = double;
```

```
using Kilogram = double;
using Pound = double;
```

```
Newton CalculateForce(Kilogram mass);


Pound mass = GetMassInPounds();
auto force = CalculateForce(mass);
```

```
class Kilogram
{
public:
    explicit Kilogram(double value) : value_(value) {}
    double get() const { return value_; }
private:
    double value_;
};
```

```
class Pound
{
public:
    explicit Pound(double value) : value_(value) {}
    double get() const { return value_; }
private:
    double value_;
};
```

```
class Kilogram
{
public:
    explicit Kilogram(double value) :
value_(value) {}
    double get() const { return value_;
}
private:
    double value_;
};
```

```
class Pound
{
public:
    explicit Pound(double value) :
value_(value) {}
    double get() const { return value_;
}
private:
    double value_;
};
```

```
class Kilogram
{
public:
    explicit Kilogram(double value) :
value_(value) {}
    double get() const { return value_;
}
private:
    double value_;
};
```

```
class Pound
{
public:
    explicit Pound(double value) :
value_(value) {}
    double get() const { return value_;
}
private:
    double value_;
};
```

```
template <typename UnderlyingType>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};
```

```cpp
template <typename UnderlyingType>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double>;
```

```cpp
template <typename UnderlyingType>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double>;
using Pound = StrongType<double>;
```

```cpp
template <typename UnderlyingType>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double>;
using Pound = StrongType<double>;
```

```cpp
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

struct KilogramParameter{};
using Kilogram = StrongType<double, KilogramParameter>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

struct KilogramParameter{};
using Kilogram = StrongType<double, KilogramParameter>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

struct KilogramParameter{};
using Kilogram = StrongType<double, KilogramParameter>;

struct PoundParameter{};
using Pound = StrongType<double, PoundParameter>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double, struct KilogramParameter>;
using Pound = StrongType<double, struct PoundParameter>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double, struct KilogramParameter>;
using Pound = StrongType<double, struct PoundParameter>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};

using Kilogram = StrongType<double, struct KilogramParameter>;
using Pound = StrongType<double, struct PoundParameter>;
```

Unit Conversion

```cpp
using namespace std::chrono;
void PrintSeconds(seconds s)
{
    std::cout << s.count() << '\n';
}

int main()
{
    hours hrs = 4h;
    PrintSeconds(hrs); // Prints 14400
}
```

```
std::ratio<3, 2>
```

```
std::ratio<60>;
```

```
std::ratio<60>;

std::ratio<60, 1>;
```

```
template <typename UnderlyingType, typename PhantomTag>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};
```

```
template <typename UnderlyingType, typename PhantomTag, typename Ratio>
class StrongType
{
public:
    explicit StrongType(UnderlyingType const& value) : value_(value) {}
    UnderlyingType get() { return value_; }
private:
    UnderlyingType value_;
};
```

```cpp
struct MassTag {};

using Gram = StrongType<double, MassTag, std::ratio<1>>;

using Kilogram = StrongType<double, MassTag, std::kilo>;
```

```
// In StrongType class definition
template <typename OtherRatio>
operator StrongType<UnderlyingType, PhantomTag, OtherRatio>()
const
{
    return StrongType<UnderlyingType, PhantomTag, OtherRatio>(
        get() *
        Ratio::num / Ratio::den *
        OtherRatio::den / OtherRatio::num
    );
}
```

```
// In StrongType class definition
template <typename OtherRatio>
operator StrongType<UnderlyingType, PhantomTag, OtherRatio>()
const
{
    return StrongType<UnderlyingType, PhantomTag, OtherRatio>(
        get() *
        Ratio::num / Ratio::den *
        OtherRatio::den / OtherRatio::num
    );
}
```

```
using Gram = StrongType<double, MassTag, std::ratio<1>>;

using Kilogram = StrongType<double, MassTag, std::kilo>;
```

```
template <typename UnderlyingType, typename PhantomTag, typename Ratio>
class StrongTypeImpl {
    ...
}

template <typename UnderlyingType, typename PhantomTag>
using StrongType = StrongTypeImpl<UnderlyingType, PhantomTag, std::ratio<1>>;
```

```
using Gram = StrongType<double, struct MassTag>;

using Kilogram = MultipleOf<Gram, std::kilo>;
```

Conversion from Pounds to Kilograms

```
using Pound = MultipleOf<Kilogram, std::ratio<56699, 125000>>;
```

Adding in base functionality

```
Gram sum = Gram(g1.get() + g2.get());
```

```
Gram sum = Gram(g1.get() + g2.get());
```

```
Gram sum = Gram(g1.get() + g2.get());
```

```
Gram sum = g1 + g2;
```

```
Gram sum = g1 + g2;
```

```
Gram sum = g1 + g2;
```

```
using Gram = StrongType<double, MassTag, Addable, Subtractable>;
```

Curiously Recurring Template Pattern!

```
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this); }
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```cpp
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this); }
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this); }
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this); }
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this);
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```cpp
template <typename Strong_Type, template<typename> class crtpType>
struct crtp
{
    Strong_Type const& underlying() const { return static_cast<Strong_Type const&>(*this); }
};

template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};

template <typename UnderlyingType, typename PhantomTag>
class StrongType : Addable<StrongType<UnderlyingType, PhantomTag>>
{
    ...
};
```

```cpp
template <typename Strong_Type>
struct Addable : crtp<Strong_Type, Addable>
{
    Strong_Type operator+(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() + other.get());
    }
};
template <typename Strong_Type>
struct Subtractable : crtp<Strong_Type, Subtractable>
{
    Strong_Type operator-(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() - other.get());
    }
};
template <typename Strong_Type>
struct Multipliable : crtp<Strong_Type, Multipliable>
{
    Strong_Type operator*(Strong_Type const& other) const {
        return Strong_Type(this->underlying().get() * other.get());
    }
};
```

```
template <typename Strong_Type>
struct Comparable : crtp<Strong_Type, Comparable>
{
    bool operator<(Strong_Type const& other) const { return this->underlying().get() < other.get(); }
    bool operator>(Strong_Type const& other) const { return other.get() < this->underlying().get(); }
    bool operator<=(Strong_Type const& other) const { return !(other.get() < this->underlying().get()); }
    bool operator>=(Strong_Type const& other) const { return !(*this < other); }
    bool operator==(Strong_Type const& other) const { return !(*this < other) && !(other.get() <
this->underlying().get()); }
    bool operator!=(Strong_Type const& other) const { return !(*this == other); }
};
```

```cpp
template <typename Strong_Type>
struct Printable : crtp<Strong_Type, Printable>
{
    void print(std::ostream& os) const { os << this->underlying().get(); }
};
```

```cpp
template <typename Strong_Type>
struct Printable : crtp<Strong_Type, Printable>
{
    void print(std::ostream& os) const { os << this->underlying().get(); }
};

using MyType = StrongType<double, struct MyTag>;

MyType m{5};
std::cout << m; // Doesn’t work :-(
```

```
template <typename UnderlyingType, typename PhantomTag>
std::ostream& operator<<(
    std::ostream& os,
    StrongType<UnderlyingType, PhantomTag> const& object
) {
    ...
}
```

```cpp
template <typename Strong_Type>
struct Printable : crtp<Strong_Type, Printable>
{
    void print(std::ostream& os) const { os << this->underlying().get(); }
};

template <typename UnderlyingType, typename PhantomTag>
std::ostream& operator<<(
    std::ostream& os,
    StrongType<UnderlyingType, PhantomTag> const& object
) {
    object.print(os);
    return os;
}
```

```cpp
template <typename Strong_Type>
struct Printable : crtp<Strong_Type, Printable>
{
    void print(std::ostream& os) const { os << this->underlying().get(); }
};

template <typename UnderlyingType, typename PhantomTag>
std::ostream& operator<<(
    std::ostream& os,
    StrongType<UnderlyingType, PhantomTag> const& object
) {
    object.print(os);
    return os;
}

using MyType = StrongType<double, struct MyTag>;

MyType m{5};
std::cout << m; // Works now :-)
```

```
using MyType = StrongType<double, struct MyPhantom, Addable, Subtractable>;
```

```
template <
    typename UnderlyingType,
    typename PhantomTag,
    template<typename> class... Skills
>
class StrongType :
    public Skills<StrongType<UnderlyingType, PhantomTag, Skills...>>...
{
    ...
};
```

```
template <
    typename UnderlyingType,
    typename PhantomTag,
    template<typename> class... Skills
>
class StrongType :
    public Skills<StrongType<UnderlyingType, PhantomTag, Skills...>>...
{
    ...
};
```

```
template <
    typename UnderlyingType,
    typename PhantomTag,
    template<typename> class... Skills
>
class StrongType :
    public Skills<StrongType<UnderlyingType, PhantomTag, Skills...>>...
{
    ...
};
```

```
template <
    typename UnderlyingType,
    typename PhantomTag,
    template<typename> class... Skills
>
class StrongType :
    public Skills<StrongType<UnderlyingType, PhantomTag, Skills...>>...
{
    ...
};
```

```
template <
    typename UnderlyingType,
    typename PhantomTag,
    template<typename> class... Skills
>
class StrongType :
    public Skills<StrongType<UnderlyingType, PhantomTag, Skills...>>...
{
    ...
};

using XType = StrongType<double, struct MyPhantom, Addable, Subtractable>;
using YType = StrongType<double, struct MyPhantom, Multipliable>;
```

Defining literals

```
Gram operator"" _grams(unsigned long long g)
{
    return Gram(g);
}
```

```
Gram operator"" _grams(unsigned long long g)
{
    return Gram(g);
}

Gram g = 3_grams;
```

```
Gram operator"" _grams(unsigned long long g)
{
    return Gram(g);
}

Kilogram k = 10_grams;
Pound p = 2_grams;
```

```
Kilogram operator"" _kilograms(unsigned long long k)
{
    return Kilogram(k);
}

Pound operator"" _pounds(unsigned long long p)
{
    return Pound(p);
}
```

Show how it all falls together

```
using Gram = StrongType<double, MassTag, Addable, Printable>;

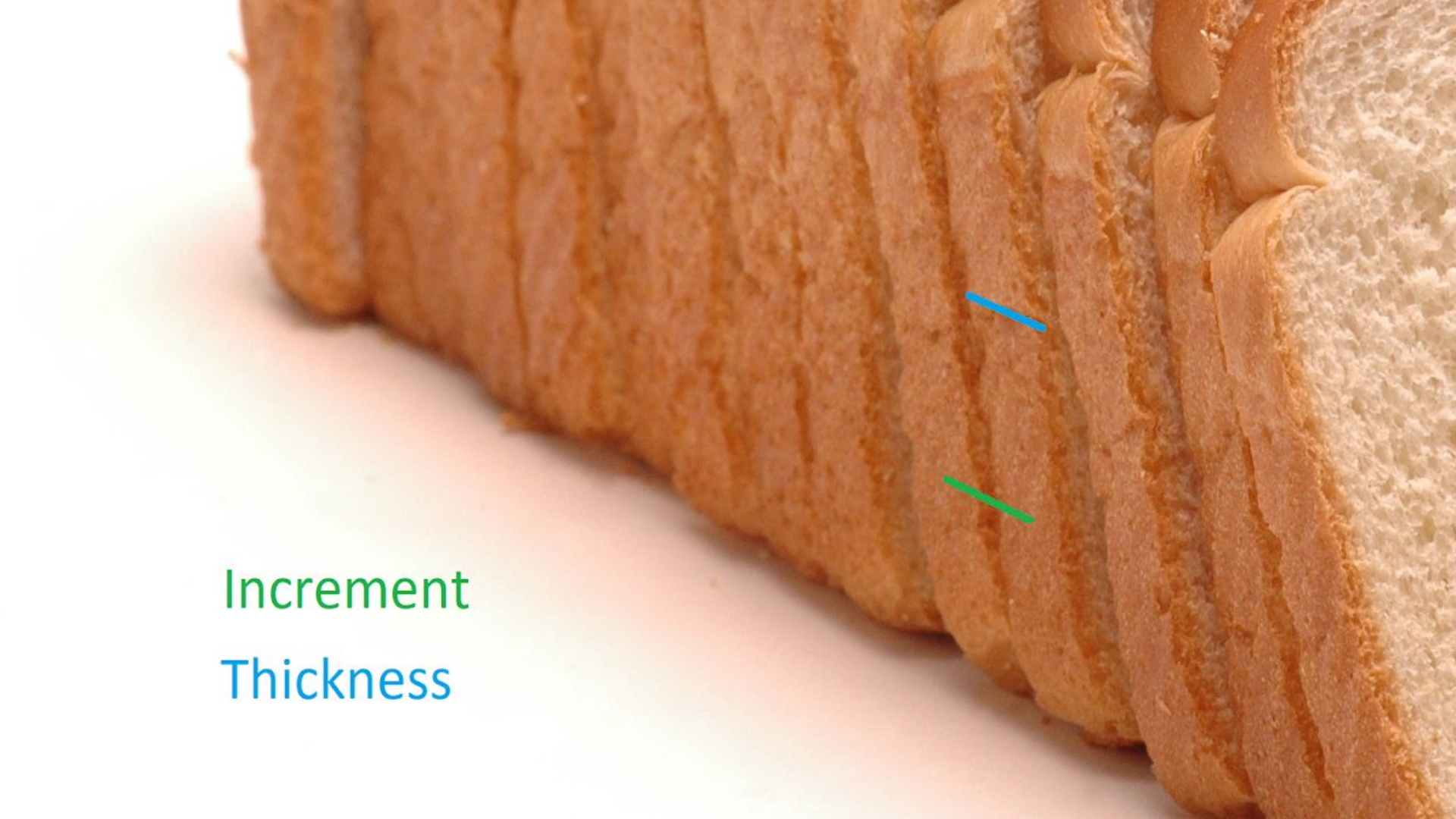
using Kilogram = MultipleOf<Gram, std::kilo>;
using Pound = MultipleOf<Kilogram, std::ratio<56699, 125000>>;

Kilogram operator"" _kilograms(unsigned long long k) {return Kilogram(k);}
Pound operator"" _pounds(unsigned long long p) {return Pound(p);}

void printMassInGrams(Gram mass) {
    std::cout << mass << "g";
}

printMassInGrams(2_kilograms + 2_pounds);
// Prints 2907.185g :-)
```

Real-World use-cases


Increment
Thickness

```
void Initialise(bool enabled, double thickness, double increment);
```

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```
// Header file:
void Initialise(bool enabled, double thickness, double increment);

// Cpp file:
void MyClass::Initialise(bool enabled, double increment, double thickness) {
    //...
}
```

```
struct StepValues {
    bool enabled;
    double thickness;
    double increment;
};

void Initialise(StepValues);
```

```
using Enabled = StrongType<bool, struct EnabledTag>;
using Thickness = StrongType<double, struct ThicknessTag>;
using Increment = StrongType<double, struct IncrementTag>;

struct StepValues {
    Enabled enabled;
    Thickness thickness;
    Increment increment;
};

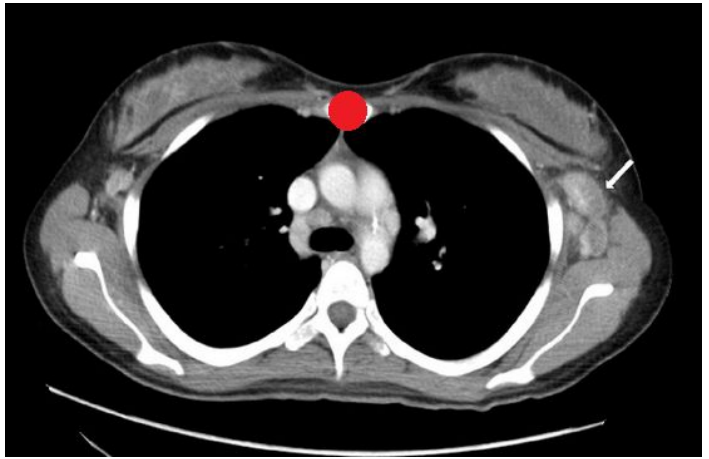
void Initialise(StepValues);
```

```
void Initialise(Enabled, Thickness, Increment);
```

```
void Initialise(Enabled, Thickness, Increment);
```

Real-World use-cases


ONE
Aquilion
10
sec
10
sec

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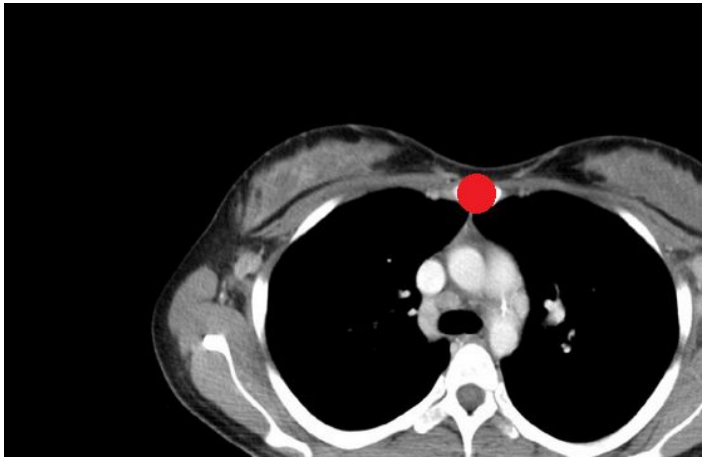

```
class Vector {
public:
    Vector(float x, float y, float z);
    float X() const;
    float Y() const;
    float Z() const;

    Vector operator +(const Vector& other) const;
    Vector operator -(const Vector& other) const;
    float Dot(const Vector& other) const;
    Vector Cross(const Vector& other) const;
    void Norm();
    float Mag();
    ...
private:
    float data[3];
};
```

```
class Matrix {
public:
    ...
    Vector Transform(const Vector& vector) const;
    Vector Transform33(const Vector& vector) const;
    ...
private:
    float data[12];
};
```

```
class TransformManager
{
public:
    ...
    Matrix GetTransform(Space from, Space to) const;
    ...
};
```

```
Vector p_patient = ...;
Vector q_patient = ...;

Vector pq_patient = q_patient - p_patient;

Matrix transform_matrix = ...;

Vector p_view = transform_matrix.Transform(p_patient);
Vector pq_view = transform_matrix.Transform33(pq_patient);

Vector broken = pq_view + q_patient; // What is this?

double m = pq_patient.Mag();
double p = pq_view.Mag();
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Understandable RayTracing in 256 lines of bare C++

https://github.com/ssloy/tinyraytracer

```
Vec3f cast_ray(
    const Vec3f &orig,
    const Vec3f &dir,
    const std::vector<Sphere> &spheres,
    const std::vector<Light> &lights,
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);
```

```
Patient::Point p_patient = ...;
Patient::Point q_patient = ...;

Patient::Vector pq_patient = q_patient - p_patient;

TransformManager helper = ...;

View::Point p_view = p_patient.ConvertTo<View>(helper);
View::Vector pq_view = pq_patient.ConvertTo<View>(helper);

auto broken = pq_view + q_patient; // Does not compile :-)

Millimetres m = pq_patient.Mag();
Pixels p = pq_view.Mag();
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Pixels p = pq_view.Mag();
```

```
error: You can't add points to vectors

...

error: You can't add vectors from different spaces
```

Conclusion

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MCO Root Cause

The MCO MIB has determined that the root cause for the loss of the MCO spacecraft was the failure to use metric units in the coding of a ground software file, “Small Forces,” used in trajectory models. Specifically, thruster performance data in English units instead of metric units was used in the software application code titled SM_FORCES (small forces). The output from the SM_FORCES application code as required by a MSOP Project Software Interface Specification (SIS) was to be in metric units of Newton-seconds (N-s). Instead, the data was reported in English units of pound-seconds (lbf-s). The Angular Momentum Desaturation (AMD) file contained the output data from the SM_FORCES software. The SIS, which was not followed, defines both the format and units of the AMD file generated by ground-based computers. Subsequent processing of the data from AMD file by the navigation software algorithm therefore, underestimated the effect on the spacecraft trajectory by a factor of 4.45, which is the required conversion factor from force in pounds to Newtons. An erroneous trajectory was computed using this incorrect data.

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Conclusion

"Culture Eats Strategy for Breakfast"

Peter Drucker

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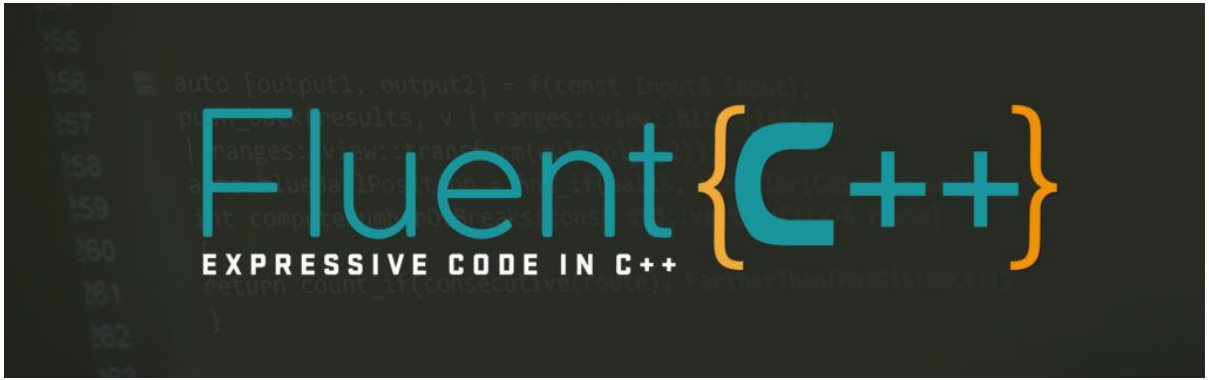
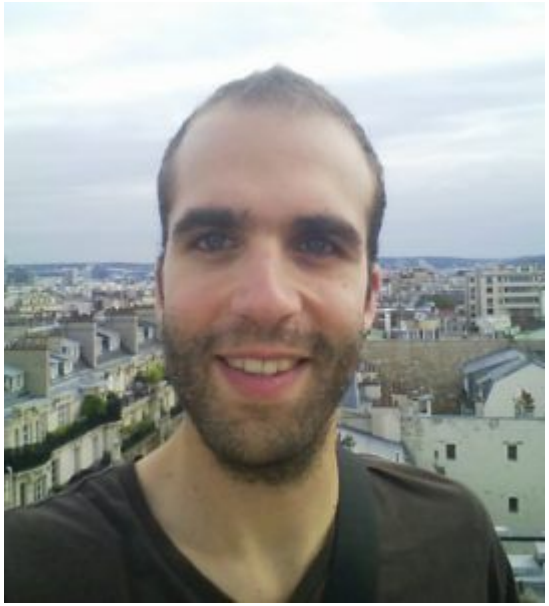
Jonathan Boccara





https://www.fluentcpp.com/posts/#strong-types

https://github.com/joboccara/StrongType

Jonathan Müller

https://foonathan.net/blog/2016/10/11/type-safe.html

https://github.com/foonathan/type_safe

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Thanks :-)

@branaby