Infrastructure Commission (INFCOM)

Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT)

Expert Team on Quality, Traceability and Calibration (ET-QTC)

Calibration of humidity instruments

Part-1: Introduction

1.1 Water vapour concepts and variables to measure

Written by Drago Groselj (ARSO)

Adapted by Javier Garcia Skabar (INTI) and Stephanie Bell (NPL)

Presented by Stephanie Bell

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Calibration of humidity instruments

Overview:

1. **Introduction**
   - **1.1 Water vapour concepts and variables to measure**
   - 1.2 Water vapour theory
   - 1.3 Humidity scales and conversions

2. **Description of technology**

3. **Calibration procedures**

4. **Humidity uncertainties**

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Concepts and definitions

What do we mean by humidity or moisture?

Water vapour mixed in a gas. Water impregnated in a body.

Water content in a solid, liquid, or gas


And for ambient humidity:

Existence of gaseous state water (vapour) in other carrier gas (air)

We quantify the amount of water in the total mixture:

Dew / Frost point temperature, relative humidity

Mixing ratio, mass per unit volume

Mole (amount) fraction $$X_{\text{vapor}} = \frac{n_v}{n_v + n_a}$$

Concepts and definitions

Dew-point (DP) temperature: is the temperature to which a humid air must be cooled for water vapour to condense into liquid water.
Temperature at which the air is saturated in equilibrium over a flat water surface.

Frost-point (FP) temperature: is the temperature to which a humid air must be cooled for water vapour form frost.
Temperature at which the air is saturated in equilibrium over a flat ice surface.

WARNING: In the range **just below 0 °C** where either frost or dew (supercooled water) can form, the dew- and the frost-point temperatures differ.

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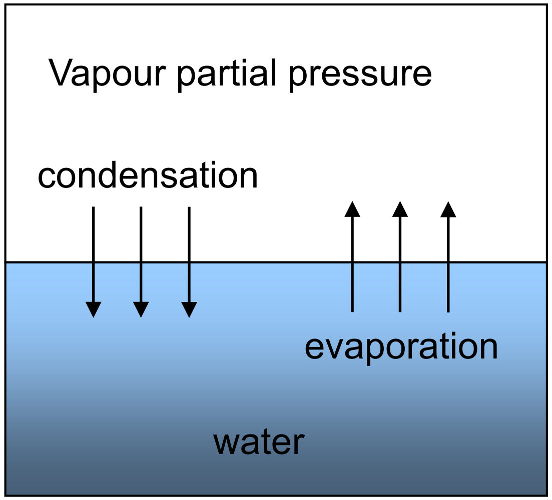
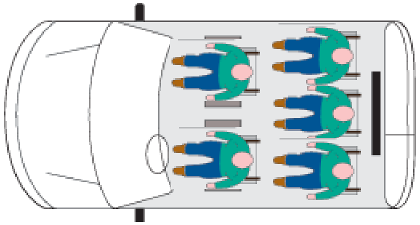
Concepts and definitions

What is saturation?

It is the result of a dynamic equilibrium and determines a maximum amount of water vapour that space can contain at a certain pressure and temperature.





total possible seats to occupy are occupied

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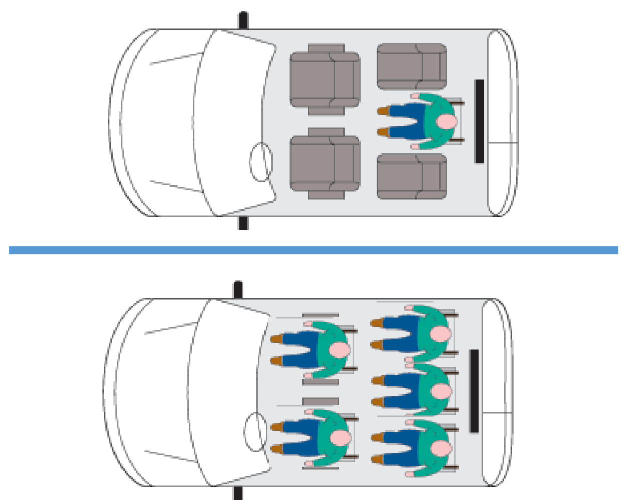
Concepts and definitions

Relative humidity (*U*): Ratio between the "current" partial vapour pressure e'(mole fraction X_v) of the mixture (air with vapour) and the saturation vapour pressure $e'_{w/i}$ (mole fraction saturation X_{vs}) over a flat surface of liquid water or ice (*w* or *i*) at the same temperature and pressure of the mixture expressed as a percentage.

$$U = \left(\frac{e'}{e'_{w/i}}\right)_{P,T} \times 100 \quad \text{or} \quad U = \left(\frac{X_v}{X_{vs}}\right)_{P,T} \times 100$$

relative occupied seats in a car (U)



current occupied seats (e and X_v)

total possible seats to occupy (e_s and X_{vs})

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Concepts and definitions

Concise version of main humidity definitions as given in WMO-No.8 (2024) Guide to Instruments and Methods of Observation, Volume 1, Chapter 4:

- ***Mixing ratio r***: ratio between the mass of water vapour and the mass of dry air;
- ***Specific humidity q***: ratio between the mass of water vapour and the mass of moist air;
- ***Dew-point temperature or dew point*** t_d: The temperature at which moist air is saturated with water vapour.
- ***Relative humidity U***: ratio in % of the observed vapour pressure to the saturation vapour pressure with respect to water at the same temperature and pressure. The term "relative humidity" is often abbreviated to RH;
- ***Vapour pressure e'*** : The partial pressure of water vapour in air;
- ***Saturation vapour pressures*** e'_w ***and*** e'_i: Vapour pressures in air in equilibrium with the surface of water and ice, respectively.

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Concepts and definitions

Commonly used units and scales relevant to humidity are given WMO-No.8 (2024) as:

- **Mixing ratio *r* and specific humidity *q*** (dimensionless quotient of masses, in kilogrammes per kilogrammes, $kg \cdot kg^{-1}$);
- **Vapour pressure in air e', e'_w, e'_i and pressure *p*** (in units of pressure, such as hectopascals, hPa. 1 hPa = 1mbar);
- **Temperature *t*, wet-bulb temperature t_w, dewpoint temperature t_d, and frost-point temperature t_f** (in degrees Celsius, °C);
- **Temperature *T*, wet-bulb temperature T_w, dewpoint temperature T_d, and frost-point temperature T_f** (in kelvins, K, as used for certain humidity calculations, and for expressing differences, rather than for general expression of humidity values);
- **Relative humidity *U*** (in percent, %. The alternative symbol, %rh*, is also often used to avoid confusion with other percentages.)

* Or %RH

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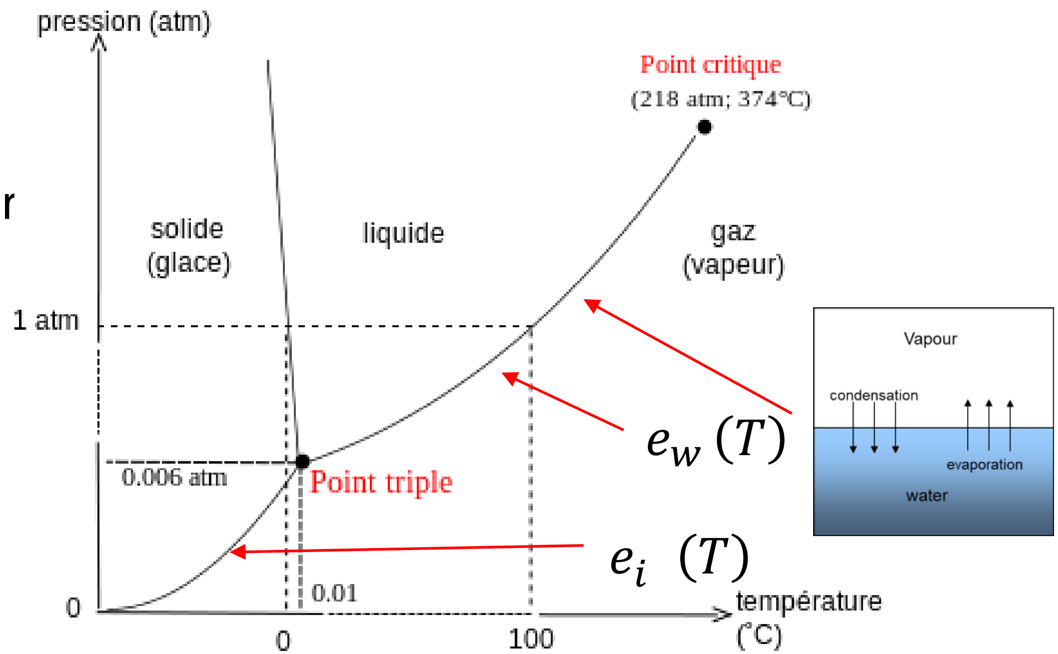
Concepts and definitions

Saturation pressure vapour, relative humidity and dew- / frost-point temperature,

One component system. Water

phase rule (Josiah Willard Gibbs 1875)
1 degree of freedom



In this system, the saturation vapour pressure depends only on the temperature

Important: We have an empirical equation for $e_{w/i}(T)$

Concepts and definitions

$$e_{w/i}(T) = exp\left(\sum_{i=0}^{6} a_i \cdot T^{i-2} + a_7 \cdot \ln(T)\right)$$ (pressure in Pa, temperature in K)

ITS-90 formulations by Hardy (1998) for vapor pressure, frost-point temperature, dew-point temperature, and enhancement factors in the range -100 to 100 ºC

Hardy R., in *Papers and Abstracts from the Third ISHM 1998;* NPL, London, 1998, 1, pp.214 222.

Or similar equation by Sonntag (1990)

Sonntag, D.; Important New Values of the Physical Constants of 1986, Vapor Pressure Formulations based on the ITS-90 and Psychrometer Formulae; Z. Meteorol., 70 (5), 1990, pp. 340-344.

The above are correct in terms of the current temperature scale (ITS-90)

(Older equations by Wexler/Greenspan are not in terms of ITS-90 but can be used approximately)

Wexler, A., Greenspan, L., in *Journal of research of NBS* 80A: 775-785 (1976).

Wexler, A., in *J.Res.Natl.Bur.Stand.A, Phys.Chem.*(USA) 81A: 5-20 (1977).

Concepts and definitions

WMO No.8 GUIDE TO INSTRUMENTS AND METHODS OF OBSERVATION - VOLUME I (2023 ed), ANNEX 4.B. FORMULAE FOR THE COMPUTATION OF MEASURES OF HUMIDITY

The following formulae (due to Magnus) are convenient for approximate calculation if the uncertainty is considered

$$e_w\,(t) = 6{,}112 \cdot exp(17{,}62 \cdot t\,/(243{,}12 + t))$$

Water, pure phase, –45 °C to +60 °C, uncertainty up to 0.6 %, (*k* = 2)

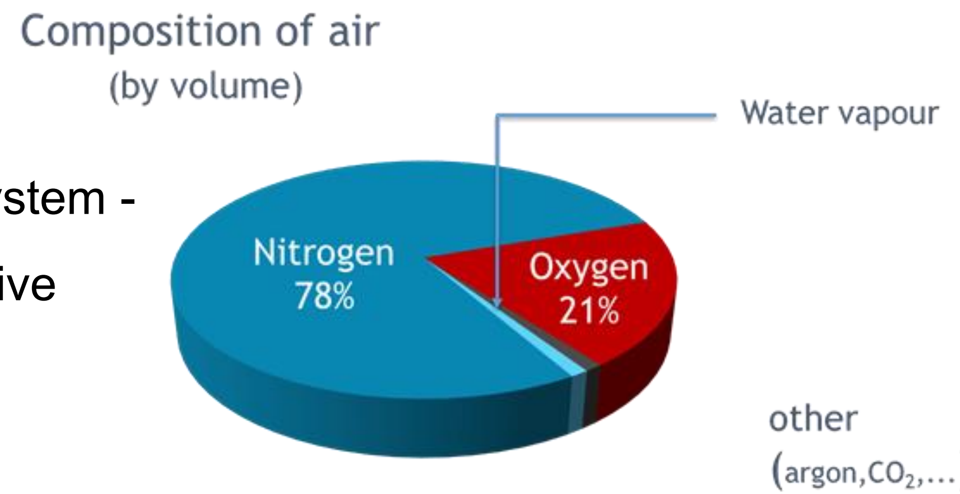
$$e_i\;\,(t) = 6{,}112 \cdot exp(22{,}46 \cdot t\,/(272{,}62 + t))$$

Ice, pure phase, –65 °C to 0 °C, uncertainty up to 1 %, (*k* = 2)

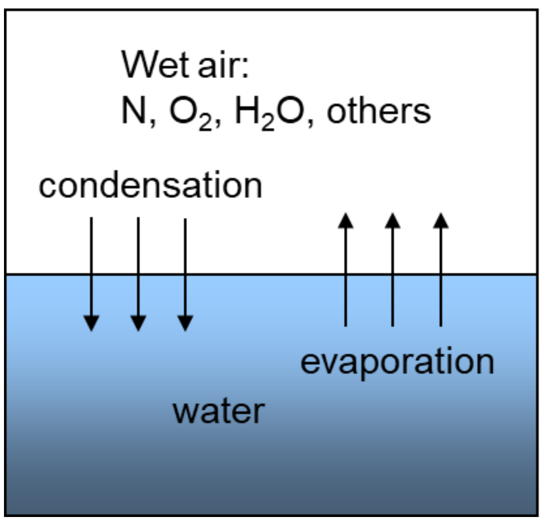
(Pressure in Pa, temperature in °C)

Warning: not for two pressure humidity generators

Concepts and definitions



Wet air is not a one-component system - two phases and various non-reactive components



These change the vapor pressure and the freedom degrees of the system.

The effective saturation vapor pressure $e'_{w/i}$ also depends on the total pressure of the system.

The empirical equation for $e_{w/i}(T)$ must be adjusted, as water vapour does not act as an "ideal gas".

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Concepts and definitions

A good approximation at atmospheric pressure and near room temperature is: $e'_{w/i}(P,T) \approx e_{w/i}(T)$

This underestimates effective vapour pressure by about 0.4 %, in room air.

For accurate calculation, an increase factor known as the *water vapour enhancement factor, f ,* must be considered due to the interaction in the air-water vapor mixture. Then:

$$e'_{w/i}(P,T) = f(P,T) \cdot e_{w/i}(T)$$

Accurate enhancement factor equations by Hardy (1998):

ITS-90 formulations for vapor pressure, frost-point temperature, dew-point temperature, and enhancement factors in the range –100 ºC to 100 ºC
Hardy R., in *Papers and Abstracts from the Third ISHM 1998;* NPL, London, 1998, 1, pp.214 222.

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Concepts and definitions

For enhancement factor, approximate calculations using older equations (pre-1990) also can be used with acceptable uncertainty.

Water vapour enhancement factor general form of equation:

$$f(P,T) = exp\left(\alpha \cdot \left(1 - \frac{e_{w/i}(T)}{P}\right) + \beta \cdot \left(\frac{P}{e_{w/i}(T)} - 1\right)\right)$$

$$\alpha = \sum_{i=0}^{3} A_i t^i \qquad \beta = e^{\sum_{i=0}^{3} B_i t^i}$$

Water 0 ºC to 100 ºC

Water –50 ºC to 0 ºC

Ice –100 ºC to 0 ºC

Hyland R. W., A correlation for the second virial coefficients and enhancement factors for CO_2-Free moist air from –50 ºC to 90 ºC, in *Journal of research of NBS*, 79A: 551-560 (1975)

Greenspan, L., Functional equations for the enhancement factors for CO_2-Free moist air, in *Journal of Research of the NBS*, 80A, 41-44 (1976).

Goff J.A. standardization of thermodynamic properties of moist air, Heating, piping and air conditioning 21, 118 (1949).

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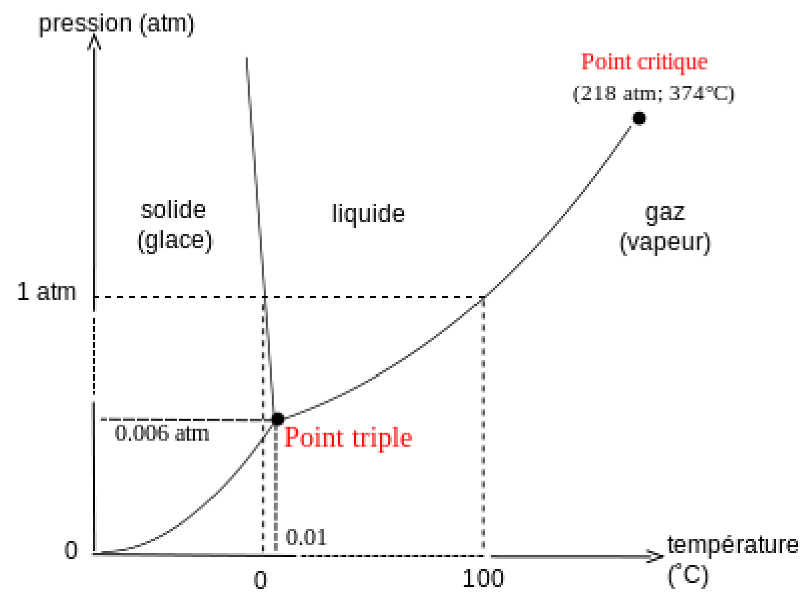
Concepts and definitions

To understand humidity scales and conversions, we combine the following concepts and definitions:

saturation vapour pressure,

the empirical equations or formulae

$$e'_{w/i}(P,T) = f(P,T) \cdot e_{w/i}(T),$$



Relative humidity $$U = \left(\frac{e'}{e'_{w/i}}\right)_{P,T} \times 100,$$

and dew / frost point temperature definitions.

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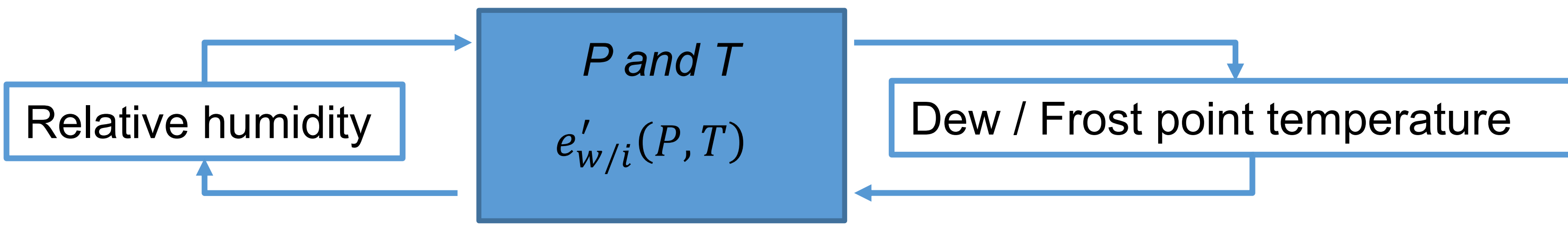
Concepts and definitions

Measuring *U* or $t_{dew/frost}$ allows indirect evaluation of other humidity variables such as vapour pressure or mixing ratio.

Conversions typically involve a vapour pressure equation.

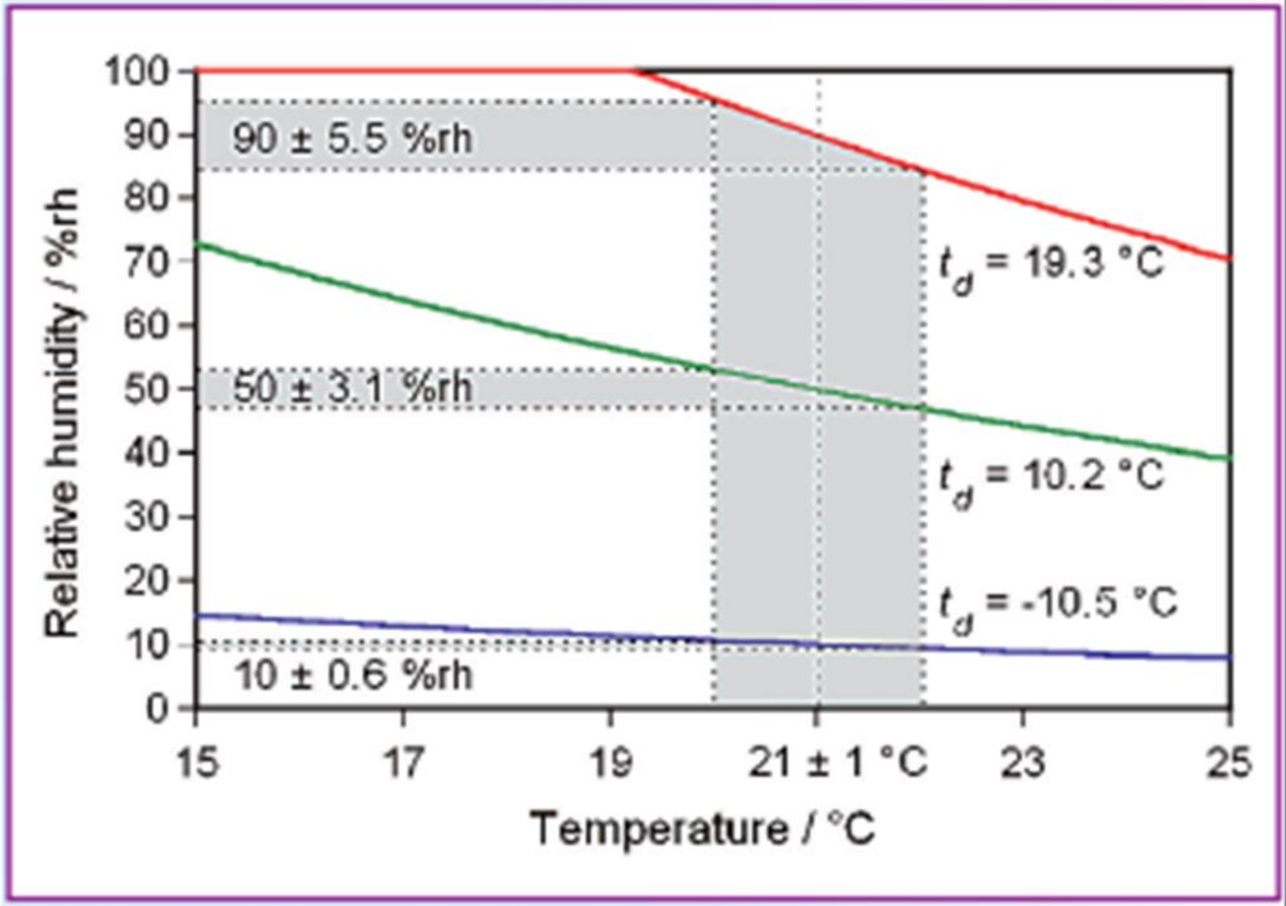
To convert from *U to* $t_{dew/frost}$, or the inverse:



The empirical equation $f(P,T)$ and $e_{w/i}(T)$ are approximations and formulas, → have uncertainty

"Fundamental" fraction or ratio in terms of mass or moles (amount) of vapour can be directly measured → otherwise, can be calculated via $f(P,T)$ and $e_{w/i}(T)$

Concepts and definitions



Relative humidity as a function of temperature for lines of constant dew-point (td). ***(see text for details)***

Ref:: Humidity hassles by Jeremy Lovell-Smith, Measurement Standards Laboratory

Concepts and definitions

Why the scale in dew point temperature?

It is based on a fundamental thermodynamic equilibrium that can be reproduced, with direct link to SI unit of temperature

- It is more direct than measuring relative humidity
- Does not depend on ambient temperature
- The technology for dew point meters is more “reliable” they are more repeatable, less long-term drift.

Thank you.

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