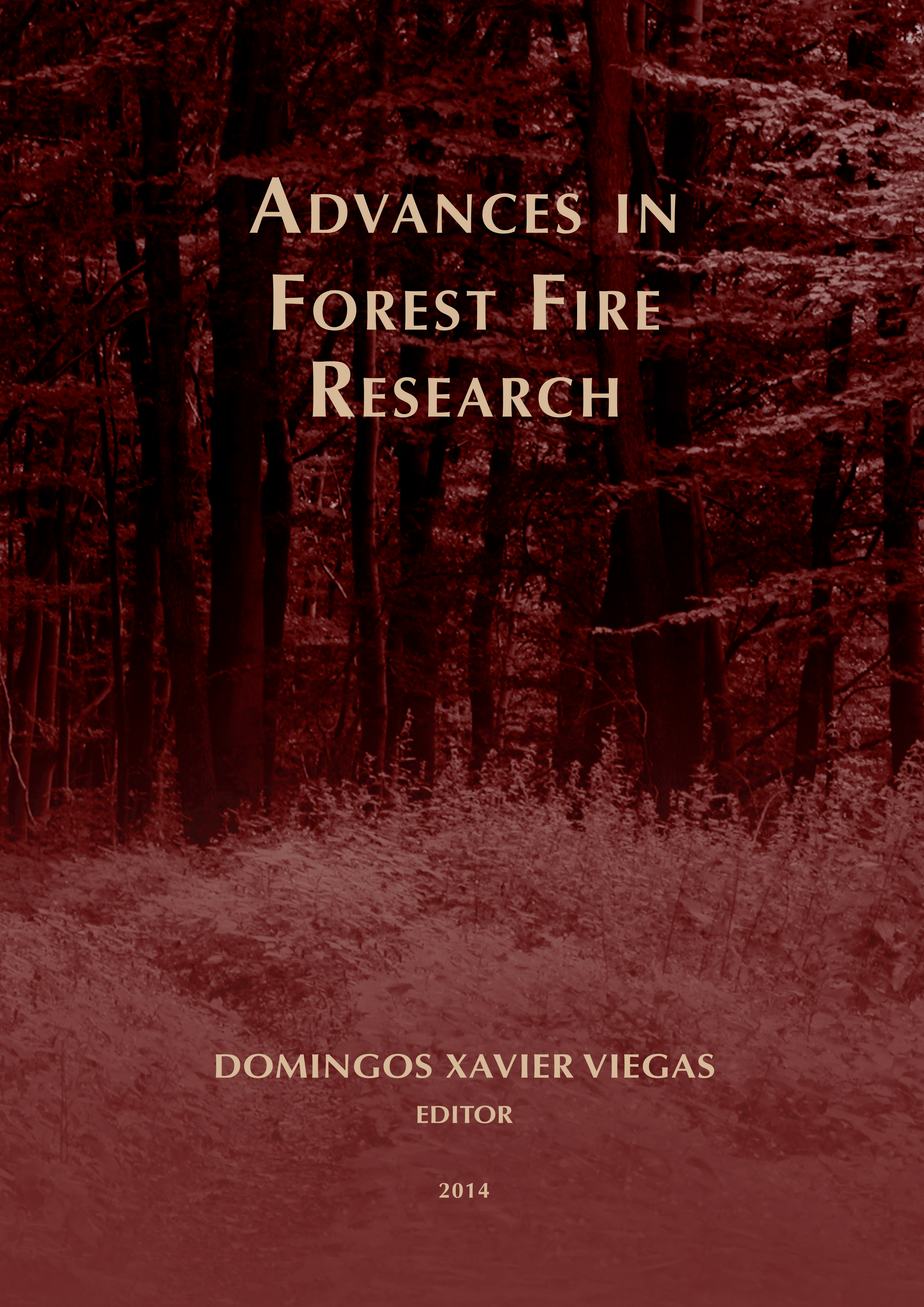

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Characteristic length of radiative ignition from wildland flames

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Abstract

The process of radiative ignition from wild land flames is studied using a simple heat transfer model. For vertical flames (no wind and no slope effects), it is found that the fuel ignition time increases exponentially with distance, which reveals the existence of a characteristic length above which no ignition occurs. The influence of flame size and fuel moisture content on this length is examined. For distances from the flame much smaller than the characteristic length, the ignition time is found to be independent of the moisture content. The existence of such a characteristic length is of major concern for studying percolation-like spread/non spread transition.

***Keywords**: Wild land flame radiation, characteristic length, ignition.*

1. Introduction

Propagation/non-propagation transition threshold is possible only for finite mean free paths [1]. A finite path length is induced by an exponentially decreasing connection probability with the distance between sites. In the frame of propagation of epidemics and forest fires, small world networks seem to be good candidates. They exhibit long-range connections [2] with an exponentially decreasing connectivity distribution. In computer networks (scale free networks), there is no percolation threshold because the connectivity distribution is power-law decreasing (the characteristic length is infinite) [2]. As stated by Albini [3] the dominant mechanism for fire spread is often radiation for the simple reason that the movement of air is toward the burning zone rather than away from it, at least in the near vicinity of the fire edge where rapid heating of unignited fuel is taking place. This situation is obtained even for wind-aided fire spread whenever the flame structure stands erect from the fuel surface rather than being blown through it. Following Billaud *et al*. [4] and Mudan [5], radiation flux is asymptotically power-law decreasing with distance. However, when studying radiative ignition of wildland fuels, a characteristic length can emerge. This is the aim of the present work. The influence of flame properties and fuel moisture content is also examined.

2. Ignition process

A simple physical model, derived from that of Koo *et al*. [6, 7], is used for steady-state contiguous fire spread in a thermally-thin uniform porous fuel bed (see Fig.1). In this model, the fuel bed is horizontal or inclined with a slope $\boldsymbol{\phi_s}$. It has a length L_{fb} and is assumed to be a thin homogenous, porous fuel layer (its thickness e is small compared to the fuel bed and flame sizes). The fuel medium is preheated to ignition by radiative heat transfer from the flaming zone and losses radiation to the ambient. The solid model of a single flame is used where the visible flame is regarded as a uniformly-radiating solid body with a cylindrical shape, of length L_f and radius r, and with thermal radiation emitted from its surface. Combustion and chemical reactions are thus assumed to be infinitely fast. The reference system is attached to the flame sheet so that the flame is fixed at $y = 0$. The ignition of a fuel bed control volume located at a constant distance y is examined., and the tilt angle of the flame $\boldsymbol{\theta}$ is caused by the wind speed $\boldsymbol{U_w}$ and the gravitational constant $\boldsymbol{g}$. It is approximated as [6]

$$\theta = \tan^{-1}[\frac{1.4\ \mathrm{U_W}}{\sqrt{\mathrm{g\ L_f}}}] \tag{1}$$

The heat supplied by the flame radiations leads to the fuel thermal degradation and to rise the temperature until it reaches the ignition temperature $\boldsymbol{T_{ign}}$. The temperature of the combustible layer is thus time and distance dependent ($\boldsymbol{T_y(t)}$). It is at room temperature $\boldsymbol{T_{rt}}$ for $\boldsymbol{y} = \infty$, and at the flame temperature $\boldsymbol{T_f}$ for $\boldsymbol{y} = \mathbf{0}$.

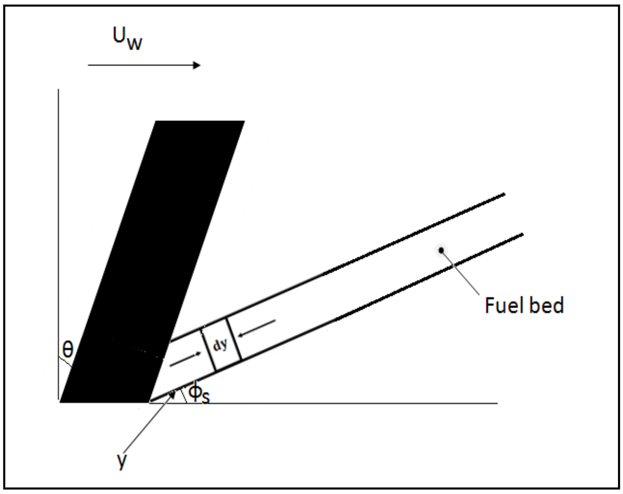

Figure 1. Planar projection of a flame spread schematic.

Consider a volume element $dy \times e \times l$ (l being the width of the fuel bed) of the combustible layer heated by a flame radiation at a distance y. Neglecting the convection flux, the total flux q_T received by this element is

$$q_T = q_{sr} + q_{rl} \tag{2}$$

The radiation flux $\mathrm{q_{sr}}$ received from the flame is defined as:

$$q_{sr} = \frac{a_{fb} \times \sigma \times \varepsilon_f \times T_f^4}{e} F \tag{3}$$

Where a_{fb} denotes the absorption coefficient of the combustible element layer, ε_f is the emissivity and σ the Stephan Boltzmann constant. The view factor (F) is determined by Monte-Carlo simulations for a cylindrical flame shape [4, 5]. The Monte-Carlo method used reduces to a stochastic ray-tracing method where discrete energy bundles are sent through the computational domain with the ray direction is sampled.

The radiation loss of the surface element q_{rl} is given by

$$q_{rl} = -\frac{\sigma \times \varepsilon_c \times (T_y^4 - T_{rt}^4)}{e} \tag{4}$$

Where ε_c denotes the emissivity of the combustible element layer. Convective heat transfer is defined as heat transfer between the fuel bed and the ambient air due to bulk fluid motion. The fuel bed may be heated or cooled by exchanging heat energy with the air by convection both on the surface and in the bulk.

The total heat flux (overhead flame radiation minus radiative losses) increases the temperature of the fuel control volume until it reaches the ignition temperature so that

$$q_T = \begin{cases} \rho_c \times C_p \times \Phi \times \frac{dT}{dt}, for\ T \neq 373^0K \\ -\rho_c \times h_{vap\times}\Phi \times \frac{dW}{dt}, for\ T = 373^0K \end{cases} \tag{5}$$

Here ρ_c is the fuel density, C_p its specific heat, Φ the volume fraction of the solid phase (fine fuel particles), W is the fuel moisture content (FMC), and h_{vap} the latent heat of water evaporation. The boundary conditions associated to Eq. (5) are

$$\begin{aligned} &T(y=0) = T_{ign}, T(y=\infty) = T_\infty \\ &W(y=0) = 0, W(y=\infty) = W_0 \end{aligned} \tag{6}$$

Here W_0 is the initial FMC, T_{ign} and T_∞ are respectively the ignition and ambient temperature. Three different heating processes appear before ignition; wet fuel preheating, drying and pyrolysis. A plateau appears at 373°K due to the phase change as shown in Fig.2.

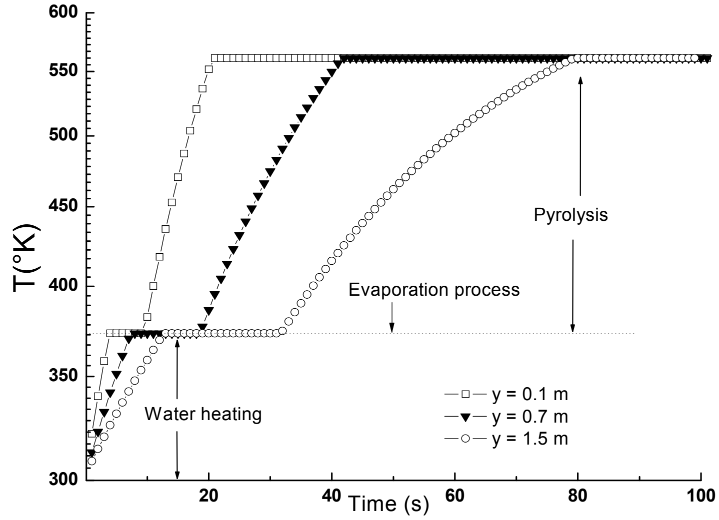

Figure 2. Time evolution of the fuel temperature for various distances y. Ignition temperature is 560°K.The water heating, evaporation and pyrolysis are shown.

3. Results

In the reference case, the flame is vertical with $L_f = 4\,m$ and $r = 1\,m$, and the FMC is 0.2. The ignition temperature is 560°K and the emissive power of the flame is $120kW/m^2$. As shown in Fig.3, above $y = 0.5m$, the ignition time exhibits an exponential increase with the distance y from the flame. It behaves as $t_{ign} \propto e^{y/l_c}$ where l_c ($l_c = 2.77 \pm 0.01m$ in Fig.3) is the characteristic ignition length. For $y > l_c$, the ignition time increases faster than the exponential increase.

The existence of a characteristic length of radiative ignition allows reducing the computational time of fire spread simulations, only a small deterministic area of radius l_c (the so-called interaction domain) being involved in the fire propagation process. This length was empirically introduced in previous studies of forest fire spread and percolation [8].

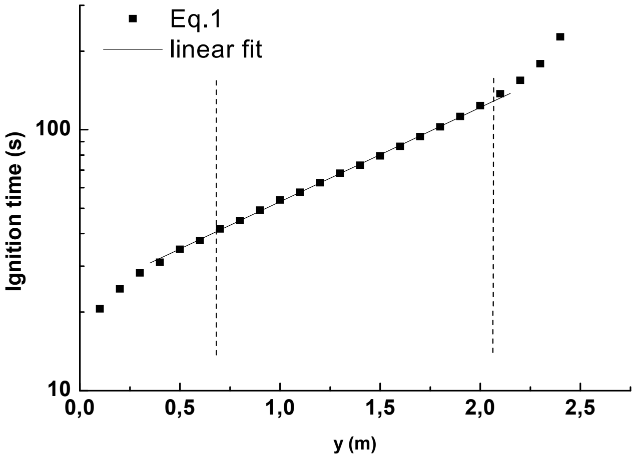

Figure 3. Ignition time vs. y.

The influence of flame height and radius on the ignition characteristic length l_c is shown in Fig.4. The characteristic length l_c increases as a power-law with the flame height. Saturation occurs for L_f around $10m$ (Fig.4a), due to the decreasing contribution of the upper part of the flame. For $L_f = 10m$, the characteristic ignition length increases logarithmically with the flame radius (Fig.4b). This logarithmic behavior indicates a slight dependence on the flame radius.

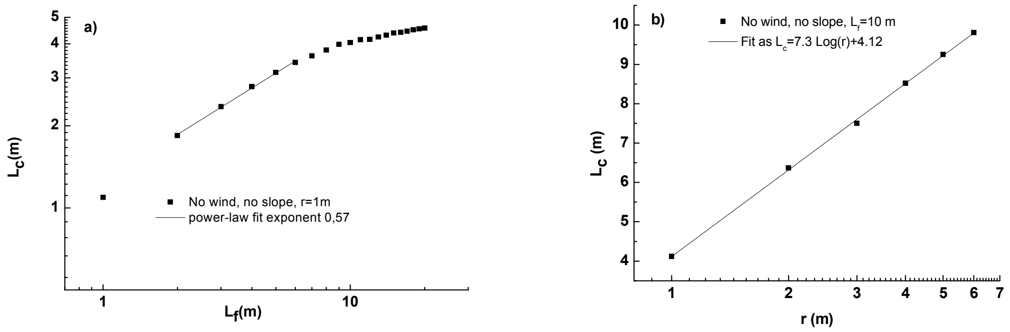

Figure 4. Characteristic length (l_c) vs. a) flame length (logarithmic plot) and b) flame radius (semi-logarithmic plot).

Ignition time increases linearly with FMC, whatever the distance from the flame (Fig.5), according as: $t_{ign} \propto FMC \times e^{y/l_c}$. This indicates that the characteristic length l_c does not depend on FMC, which only delays the ignition time. This result does not agree with the trends obtained experimentally by Trabaud [9], indicating a critical moisture content FMC_{max} above which ignition cannot occur

$$t_{ign} \propto \frac{1}{FMC_{max} - FMC} \tag{7}$$

One of the reasons of this discrepancy is the high flux and small distance y to the flame. Furthermore, flammable gas emission may occur during water heating before evaporation so that, at ignition temperature the remaining gases become insufficient for igniting the fuel. This effect is being included in the present model.

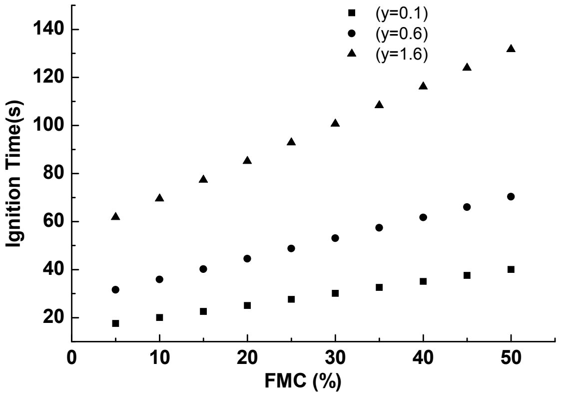

Figure 5. Ignition time dependence on the fuel moisture content for various distances from the flame.

4. Conclusions

Using a simple thermal model, the existence of a characteristic length of radiative ignition was demonstrated. The dependence of this length on the flame height and radius was investigated. It is also found that this characteristic length was independent of the fuel moisture content. Wind and slope effects on the characteristic length are currently studying.

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